Constraining Physics Beyond the Standard Model in Post-Higgs Era

A thesis submitted in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

by

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2016

to

my parents

&

teachers

Declaration

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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CERTIFICATE

It is certified that the work contained in the thesis titled **"Constraining Physics Beyond the Standard Model in Post-Higgs Era "** by **Tanmoy Mondal** (11330016), has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

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Publications

Publications included in the thesis

1. Joydeep Chakrabortty, Partha Konar and **Tanmoy Mondal**:
   Constraining a class of B-L extended models from vacuum stability and perturbativity,
   Phys.Rev. D **89**, 056014 (2014)

2. Joydeep Chakrabortty, Partha Konar and **Tanmoy Mondal**:
   Copositive Criteria and Boundedness of the Scalar Potential
   Phys.Rev. D **89**, 095008 (2014)

3. Kaushik Bhattacharya, Joydeep Chakrabortty, Suratna Das and **Tanmoy Mondal**:
   Higgs vacuum stability and inflationary dynamics after BICEP2 and PLANCK dust polarisation
   JCAP 1412 (2014) 12, 001

4. Gulab Bambhaniya, Subrata Khan, Partha Konar and **Tanmoy Mondal**:
   Constraints on a seesaw model leading to Quasi-Degenerate neutrinos and signatures at the LHC
   Phys.Rev. D **91**, 095007 (2015)

5. Ujjal Dey, Partha Konar and **Tanmoy Mondal**:
   Unitarity constraints and Charge Breaking minima in left right symmetric model
   Phys.Rev. D **92**, 096005 (2015)

Publications not included in thesis

- Tanushree Basak and **Tanmoy Mondal**:
  Constraining Minimal $U(1)_{B-L}$ model from Dark Matter Observations
  Phys.Rev. D **89** 063527, (2014)

- Tanushree Basak and **Tanmoy Mondal**:
  Class of Higgs-portal Dark Matter models in the light of gamma-ray excess from Galactic center
  Phys.Lett. B 744 (2015) 208-212

- Gulab Bambhaniya, Srubabati Goswami, Subrata Khan, Partha Konar and **Tanmoy Mondal**:
  Looking for hints of a reconstructible seesaw model at the Large Hadron Collider
  Phys.Rev. D **91** 075007, (2015)

Acknowledgements

This thesis would not have come to reality without the help, support and guidance of many people. I would like to express my gratitude towards all of them in this opportunity.

First and foremost I wish to express my sincere thanks to my supervisor, Dr. Partha Konar. It was a great experience to work under his supervision. His continuous support and constant encouragement regarding thesis related study made my research possible. He has been the epitome of friend, philosopher and guide through my years at PRL.

I take this opportunity to thank thank Prof. Srubabati Goswami for her advices at different stages of my thesis. It was a great experience to collaborate with her. I thank my collaborator Prof. Joydeep Chakrabortty for his support starting from the very beginning of my research carrier. It was a pleasure to work with Dr. Tanushree Basak, Dr. Gulab Bambhaniya and Dr. Subrata Khan.

I convey my sincere thanks to my Doctoral Studies Committee, Prof. Saurabh Rindani and Prof. Srubabati Goswami for evaluating my work in a regular basis. Their valuable comments help me to improve scientific outcomes. Also I am grateful to them for the examination of this thesis.

I thank Abhaya Kumar Swain and Gulab Bambhaniya for innumerable discussions sessions regarding thesis related and non thesis related discussions. I thank my office-mates Abhaya, Gulab, Monojit, Ujjal, Lata and Akanksha for the time with laughter, mutual encouragement and support. Also I am grateful to Ujjal and Gulab for the proofreading of this thesis.

I thank former area chairman Prof. S. Mohanty and current area chairman, Prof. H. Mishra for providing necessary facilities to carry out research work. The Theoretical Physics (THE-PH) division provided me a nice research environment which I always enjoyed. I express my gratitude to all the past and present members of the division: Dr. D. Angom, Dr. N. Mahajan, Dr. R. Rangarajan, Dr. N Singh, Dr. B. Sahoo, Prof. A. Joshipura, Prof. J. Bhatt, Razaahmed Z Maniar, Bhagyashree, Khushbu and Sujata Krishna.

It would have been impossible to pass the five years without the joyful company Abhaya, Alok, Anirban, Arun, Chithrabhanu, Gaurava, Girish, Guruprasad, Ikshu, Kuldeep, Manu, Sanjay and Shraddha.

I convey my sincere thanks to my seniors and juniors for an enjoyable hostel environment. I enjoyed very much the philosophical discussions with Amrendra and mythological discussions with Upendra, Monojit and Wagheesh.

Thanks to my M.Sc friends at IIT Madras, special thanks to Anirban, Debasis,

Dipankar, Madhumita, Nabadyuti Subhajit, Sayani and Ushasi. I express my gratitude to Prof. M. Pattabiraman, our M.Sc supervisor for his advices regarding PhD.

I spend a lot of time Googling and without it the thesis would have been impossible. I am grateful to 9gag[*], *PHD(Piles Higher and Deeper)*[†], *WBH(Wait-But-Why)* [‡], *xkcd*[§] *and Vsauce*[¶] *for helping me to keep calm and do research.*

I am grateful to Indian Institute of Technology, Gandhinagar (IIT Gn) for my registration.

I thank entire family of PRL for all the research facilities and for providing and excellent hostel facility at Thaltej.

Last, but not the least, I would like to thank my family; without their love and support it would have been impossible to reach here.

(Tanmoy)

[*] www.9gag.com
[†] www.phdcomics.com
[‡] www.waitbutwhy.com
[§] http://xkcd.com/
[¶] https://www.youtube.com/user/Vsauce

Abstract

In the history of elementary particle physics, the discovery of the Higgs boson at the Large Hadron Collider (LHC) in July 4, 2012 is an important breakthrough which completes the Standard Model (SM) of particle physics. Nevertheless, there exist experimental observations which cannot be explained by the SM, like the neutrino oscillations, dark matter, baryon asymmetry etc. With these experimental shortcomings it is evident that there exist some beyond the Standard Model (BSM) physics. There are several ways to extend the SM to explain some of the experimental phenomena which is still to be observed in the state-of-the-art experiment like LHC. But the recent Higgs discovery can shed some light in the uncharted territory of theoretical physics. We are living at a minima of the Higgs potential where the Higgs field acquires a vacuum expectation value (vev) which is intertwined with the Higgs boson mass (m_H) measured at the LHC. The stability of the minimum is ensured by the condition that the Higgs quartic coupling should be positive. But recent observation of m_H at the LHC indicates that the SM minima does not remain stable upto the Planck scale. This also indicates that there must be some new physics phenomena which will stabilize the minimum. Hence the stability analysis of the BSM scenarios is necessary to constrain parameters of the model. There are other constraints like perturbativity and unitarity of scattering amplitudes of longitudinal gauge boson modes which will also restrict the parameter space.

The BSM models that include many scalar fields posses scalar potential with many quartic couplings. Due to the complicated structures of such scalar potentials it is indeed difficult to adjudge the stability of the vacuum. Thus one needs to formulate a proper prescription for computing the vacuum stability criteria. We have used the idea of copositive matrices to deduce the conditions that guarantee the boundedness of the scalar potential. We have discussed the basic idea behind the copositivity and then used that to determine the vacuum stability criteria for the Left-Right symmetric models with doublet, and triplet scalars and Type-II seesaw. As this idea is based on the strong mathematical arguments it helps to compute simple and unique stability criteria embracing the maximum

allowed parameter space.

We study the $B-L$ gauge extension of the Standard Model which contains a singlet scalar and three right-handed neutrinos. The vacuum expectation value of the singlet scalar breaks the $U(1)_{B-L}$ symmetry. The $B-L$ symmetry breaks when the complex singlet scalar acquires a *vev*. We studied two different cases of $B-L$ breaking scale: TeV scale and $\sim 10^{10}$ GeV. The TeV scale breaking scenario can have signatures at the LHC and we have constrained parameter space of this model. The high scale breaking scenario provides a constrained parameter space where both the issues of vacuum stability and high-scale inflation can be successfully accommodated.

The Left-Right symmetric model (LRSM) is theoretically well motivated and also contains rich phenomenology. We used idea of copositivity to calculate vacuum stability conditions for two variants of the LRSM. We incorporate the unitarity conditions in LRSM which can translate into giving a stronger constraint on the model parameters together with the criteria derived from vacuum stability and perturbativity. In this light, we demonstrate the bounds on the masses of the physical scalars present in the model and find the scenario where multiple scalar modes are in the reach of Large Hadron Collider.

We have also studied a variant of TeV scale seesaw model in which three additional heavy right handed neutrinos are added to the standard model to generate the quasi-degenerate light neutrinos. This model is theoretically interesting since it can be fully rebuilt from the experimental data of neutrino oscillations except for an unknown factor in the Dirac Yukawa coupling. We study the constrains on this coupling coming from meta-stability of electro-weak vacuum. Even stronger bound comes from the lepton flavor violating decays on this model, especially in a heavy neutrino mass scenario which is within the collider reach. Bestowed with these constrained parameters, we explore the production and discovery potential coming from these heavy neutrinos at the 14 TeV run of Large Hadron Collider. Signatures with tri-lepton final state together with backgrounds are considered in a realistic simulation.

Keywords: Vacuum Stability, Copositivity, Extended Scalar Sector, Beyond the Standard Model, Z' Model, B-L symmetry, Left-Right symmetry, TeV scale seesaw, Quasi-degenerate neutrinos, Collider Phenomenology

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List of Abbreviations

SM	Standard Model
BSM	Beyond the Standard Model
QCD	Quantum ChromoDynamics
GWS	Glashow-Weinberg-Salam
EW	Electro-Weak
EWSB	Electro-Weak Symmetry Breaking
LHC	Large Hadron Collider
ATLAS	A Toroidal LHC ApparatuS
CMS	Compact Muon Solenoid
LQT	Lee-Quigg-Thacker
LH	Left Handed
RH	Right Handed
LRSM	Left Right Symmetric Model
MLRSM	Minimal LRSM
LRT	LR Model with Triplet Scalars
LRD	LR Model with Doublet Scalars
vev	Vacuum Expectation Value
COP	Copositivity
$B - L$	Baryon number minus Lepton number
GUT	Grand Unified Theory
RGE	Renormalization Group Equation
CMBR	Cosmic Microwave Background Radiation
2HDM	Two Higgs Doublet Model
LFV	Lepton Flavor Violation
VBF	Vector Boson Fusion
QD	Quasi Degenerate

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