Matheus Hostert

A Thesis presented for the degree of
Doctor of Philosophy

Durham
University

Institute for Particle Physics Phenomenology
Department of Physics
Durham University
United Kingdom

April 2019

Matheus Hostert

Submitted for the degree of Doctor of Philosophy

April 2019

**Abstract:** This is some abstract about this thesis.

*Dedicated to*

Bárbara, Humberto and Luciana.

# Contents

**Abstract** **3**

**List of Figures** **9**

**List of Tables** **11**

**1 Introduction** **19**

1.1 The Standard Model at 51 . . . . . . . . . . . . . . . . . . . . 20

1.1.1 Fields and symmetries . . . . . . . . . . . . . . . . . . . 20

1.1.2 Spontaneous symmetry breaking . . . . . . . . . . . . . 20

1.1.3 Shortcomings . . . . . . . . . . . . . . . . . . . . . . . . 20

1.2 Portals to beyond the Standard Model . . . . . . . . . . . . . . 20

**2 Aspects of neutrino physics** **21**

2.1 Oscillations . . . . . . . . . . . . . . . . . . . . . . . . . . . . 22

2.2 Sources . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 22

2.3 Scattering . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 22

2.4 Mass mechanisms . . . . . . . . . . . . . . . . . . . . . . . . . 22

2.4.1 Conventional seesaws . . . . . . . . . . . . . . . . . . . . 22

2.4.2 Low scale seesaw variants . . . . . . . . . . . . . . . . . 22

2.4.3 Radiative masses . . . . . . . . . . . . . . . . . . . . . . 22

**3 New forces in Neutrino Scattering** **23**

**4 A dark neutrino sector** **25**

**5 The MiniBooNE experimental anomaly** **27**

**6 Future precision neutrino physics** **29**

**7 Conclusions** **31**

**A Phase Space** **33**

A.1 Factorization into 2PS . . . . . . . . . . . . . . . . . . . . . 34

A.2 Three-body phase space . . . . . . . . . . . . . . . . . . . . . 34

A.3 Four-body phase space . . . . . . . . . . . . . . . . . . . . . 34

**B One loop $\nu$ masses in Type-I seesaw** **35**

B.1 Type-I seesaw neutrino masses in the SM . . . . . . . . . . . . . 36

# List of Figures

# List of Tables

# Declaration

The work in this thesis is based on research carried out in the Department of Physics at Durham University. No part of this thesis has been submitted elsewhere for any degree or qualification.

# Acknowledgements

I would like to thank my supervisor Silvia Pascoli for her continued support during my studies. I am thankful to have had Peter Ballett as a supervisor and colleague during my studies. Your passion was truly admirable and contagious, thank you.

*"It seems very pretty, […] somehow it seems to fill my head with ideas—only I don't exactly know what they are!*

— from *Through the Looking-Glass, and What Alice Found There* by Lewis Carroll

# Chapter 1

# Introduction

## 1.1 The Standard Model at 51

### 1.1.1 Fields and symmetries

### 1.1.2 Spontaneous symmetry breaking

### 1.1.3 Shortcomings

## 1.2 Portals to beyond the Standard Model

# Chapter 2

# Aspects of neutrino physics

## 2.1 Oscillations

## 2.2 Sources

## 2.3 Scattering

## 2.4 Mass mechanisms

For a review on low-scale models see [1].

### 2.4.1 Conventional seesaws

### 2.4.2 Low scale seesaw variants

### 2.4.3 Radiative masses

The most straightforward extension of the SM which can generate neutrino masses at loop level is perhaps the so-called Zee-Babu model.

# Chapter 3

# New forces in Neutrino Scattering

# Chapter 4

# A dark neutrino sector

# Chapter 5

# The MiniBooNE experimental anomaly

# Chapter 6

# Future precision neutrino physics

# Chapter 7

# Conclusions

Particle physics is at a very important moment of its history. The Standard Model has surprised us with its unprecedent accuracy in describing particle data, but a few mysteries remain. Perhaps neutrino masses and dark matter are to the Standard Model what blackbody radiation was to classical physics in the beginning of the 20th century, a scientific revolution on the wait.

# Appendix A

# Phase Space

In this appendix we show explicitly the factorization of $N$-final state phase space factors into $N-2$ 2-body ones. To study arbitrary observales that depend on the final state momenta, one must also be able to write down the four momenta in terms of the phase space variables. We carry out this exercise for 3 and 4 body phase space below.

## A.1 Factorization into 2PS

The final decomposition of the phase space factors then reads:

$$\mathrm{d}PS^2 = \mathrm{d}m^2 \mathrm{d}PS^2(p_1, p_2 3) PS^2(p_2, p_3). \tag{A.1.1}$$

## A.2 Three-body phase space

## A.3 Four-body phase space

# Appendix B

# One loop $\nu$ masses in Type-I seesaw

## B.1 Type-I seesaw neutrino masses in the SM

In this appendix, we compute the one-loop corrections to the light neutrino masses in the SM, following [2–4].

We will also be making use of the On-Shell (OS) renormalization scheme, known . This is ensured by requiring that the off-diagonal elements of the self-energy be diagonal when the external particles are on their mass shell, and that the residue of the renormalized propagator are equal to one.

Assuming Majorana neutrino fields, one can write the self-energy tensor in its most general form:

$$\Sigma_{ij}(\not{q}) = \not{q}\mathrm{P}_L\Sigma^L_{ij}(q^2) + \not{q}\mathrm{P}_R\Sigma^R_{ij}(q^2) + \mathrm{P}_L\Sigma^M_{ij}(q^2) + \mathrm{P}_R\Sigma^{M*}_{ij}(q^2), \tag{B.1.1}$$

where by virtue of the Majorana nature the previous terms obey

$$\Sigma^L_{ij}(q^2) = \Sigma^{R*}_{ij}(q^2), \qquad \Sigma^M_{ij}(q^2) = \Sigma^M_{ji}(q^2).$$

$$\delta m_L = \tag{B.1.2}$$

# Bibliography


[1] S. M. Boucenna, S. Morisi and J. W. F. Valle, *The low-scale approach to neutrino masses*, *Adv. High Energy Phys.* **2014** (2014) 831598, [1404.3751].

[2] B. A. Kniehl and A. Pilaftsis, *Mixing renormalization in Majorana neutrino theories*, *Nucl. Phys.* **B474** (1996) 286–308, [hep-ph/9601390].

[3] W. Grimus and L. Lavoura, *One-loop corrections to the seesaw mechanism in the multi-Higgs-doublet standard model*, *Phys. Lett.* **B546** (2002) 86–95, [hep-ph/0207229].

[4] D. Aristizabal Sierra and C. E. Yaguna, *On the importance of the 1-loop finite corrections to seesaw neutrino masses*, *JHEP* **08** (2011) 013, [1106.3587].