
WIP: Work in Progress Title



LUDWIG-MAXIMILIANS-UNIVERSITY MUNICH
FACULTY OF PHYSICS

DISSERTATION

Eric Schanet

December 2020

WIP: Work in Progress Title



LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
FAKULTÄT FÜR PHYSIK

DISSERTATION

Eric Schanet

December 2020

Supervisor: Prof. Dr. Dorothee Schaile

Abstract

My abstract

Zusammenfassung

Meine Zusammenfassung

Contents

1	Theory	5
1.1	The Standard Model of Particle Physics	5
1.1.1	Particle content of the SM	6
1.1.2	Quantum field theories	7
1.1.3	Renormalisation	8
1.2	Supersymmetry	8
2	The LHC and ATLAS	9
3	Data and Monte Carlo Simulation	11
3.1	Data	11
4	Statistical data analysis	13
5	Analysis	15
6	Summary	17
	Bibliography	19
	Symbols	21
	Appendix A	23
A.1	N-1 plots for cut-scan results	23
	Appendix B	25
B.1	Scatter plots comparing truth and reco yields in the SRs	25

Notes

1

Couplings and masses are measured from experiment	5	2
Neutrino masses not in SM!	6	3
need ref	6	4
Need ref	6	5
Might want to explain this later once I introduced the gauge groups?	7	6
need ref	7	7
Explicitly derive the Euler-Lagrange equations? Cf. Peskins Ch.2.2.	7	8

Introduction

1

Here is my introduction

2

Chapter 1

Theory

This chapter outlines the basic principles

1.1 The Standard Model of Particle Physics

By the end of the 1920s, quantum mechanics and general relativity had been relatively well established and the consensus among physicists was that matter was made of nuclear atoms consisting of electrons and protons. During the 1930s, a multitude of new experimental discoveries and theoretical puzzles excited physicists in three main fields of research: nuclear physics, cosmic rays and relativistic quantum mechanics. The following years and decades saw particle physics emerge as a result of these currents ultimately flowing together.

Since these early times of particle physics research, physicists have made extraordinary progress in describing nature at the subatomic scale. Today, a century later, the resulting theoretical framework, the Standard Model of Particle Physics (SM), is the most fundamental theory of nature to date. It provides an extremely precise description of the interactions of elementary particles and—using the Large Electron Positron collider (LEP)—has been tested and verified to an unprecedented level of accuracy up to the electroweak (EWK) scale. Given the unprecedented success of SM, it is not surprising that its history is paved with numerous awards for both experimental and theoretical work. In 1964, the Nobel prize was awarded to Feynman, Schwinger and Tomonaga for their fundamental work in quantum electrodynamics (QED). This quantum field theory allows to precisely calculate fundamental processes as e.g. the anomalous magnetic moment of the electron to a relative experimental uncertainty of 2.3×10^{-10} [1]. In 1979, Glashow, Weinberg and Salam were awarded with the Nobel prize for their work towards electroweak unification. The most prominent recent progress is undoubtedly the discovery of the Higgs boson, not only resulting in the Nobel prize being awarded to Englert and Higgs, but also completing the SM, roughly 50 years after the existence of the Higgs boson had been theorised.

Couplings and masses are measured from experiment

Table 1.1: Names, electric charges and masses (rounded to three significant digits if known to that precision) of all observed fermions in the SM [2].

	generation	particle	electric charge [e]	mass
leptons	1	electron (e)	-1	511 keV
		electron neutrino (ν_e)	0	< 2 eV
	2	muon (μ)	-1	106 MeV
		muon neutrino (ν_μ)	0	< 0.19 MeV
	3	tau (τ)	-1	1.78 GeV
		tau neutrino (ν_τ)	0	< 18.2 MeV
quarks	1	up (u)	$\frac{2}{3}$	2.3 MeV
		down (d)	$-\frac{1}{3}$	4.8 MeV
	2	charm (c)	$\frac{2}{3}$	1.28 GeV
		strange (s)	$-\frac{1}{3}$	95 MeV
	3	top (t)	$\frac{2}{3}$	173 GeV
		bottom (b)	$-\frac{1}{3}$	4.18 GeV

1.1.1 Particle content of the SM

The SM successfully describes ordinary matter as well as their interactions, namely the electromagnetic, weak and strong interactions. Gravity is the only fundamental force not described within the SM. The particles in the SM are classified into two main categories, depending on their spin. Particles with half-integer spin follow Fermi-Dirac statistics and are called fermions. As they are subject to the Pauli exclusion principle, they make up ordinary matter. Particles with integer spin follow Bose-Einstein statistics and mediate the fundamental interactions between fermions. All particles known to the SM are listed in tables 1.1 and 1.2.

Fermions are further divided into leptons and quarks, which each come in three generations with increasing masses[†]. The three electrically charged leptons are each associated with a corresponding neutral neutrino (more on this *association* in chapter). While the SM assumes massless neutrinos, the observation of neutrino oscillations [3] implies the existence of at least two massive neutrinos. By extending the SM to allow non-vanishing neutrino masses, neutrino oscillations can be introduced through lepton generation mixing, described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [4]. Apart from an electric charge, the six quarks also carry a colour charge. There are three types of colour charge: *red*, *green* and *blue* as well as their respective anti-colours. The mixing in the quark sector through the weak interaction can be described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [5]. Finally, each fermion comes with its own anti-particle with same mass and spin, but inverted charge-like quantum numbers[§].

[†] Neutrinos might not exist in a normal mass hierarchy but could also have an inverted mass hierarchy.

[§] The exact nature of anti-neutrinos is still an open question and ties into whether or not the neutrino mass matrix contains non-vanishing Majorana mass terms.

The fundamental forces described by the SM are propagated by bosons with spin $1\hbar$. The photon γ couples to electrically charged particles and mediates the electromagnetic interaction. As the photon is massless, the electromagnetic force has infinite range. The strong force is mediated by gluons carrying one unit of colour and one unit of anti-colour. Due to colour-confinement, colour charged particles like quarks and gluons cannot exist as free particles and instead will always form colour-neutral bound states. Although nine gluon states would theoretically be possible, only eight of them are realised in nature: the colour-singlet state $\frac{1}{\sqrt{3}}(|r\bar{r}\rangle + |g\bar{g}\rangle + |b\bar{b}\rangle)$ would be colour-neutral result in long-range strong interactions, which have not been observed. Finally, the weak force is mediated by a total of three bosons, two charged W -bosons W^+ and W^- , and a neutral Z -boson. The mediators of the weak force are massive, resulting in a finitely ranged interaction. The W^\pm and Z bosons gain their masses through the Higgs mechanism (discussed in chapter), resulting in a massive spin-0 boson, called the Higgs boson.

need ref

Might want to explain this later once I introduced the gauge groups?

need ref

1.1.2 Quantum field theories

The following theoretical descriptions and notations largely follow [6].

Formally, the SM is a collection of a special type of quantum field theories, called gauge theories. Conceptually, quantum field theory (QFT) is the application of quantum mechanics to dynamical systems of fields, just as quantum mechanics is the quantisation of dynamical systems of particles. QFT provides a uniform description of quantum mechanical particles and classical fields, while including special relativity.

In classical mechanics, the fundamental quantity is the action S , which is the time integral of the Lagrangian L , a functional characterising the state of a system of particles in terms of generalised coordinates q_1, \dots, q_n . In field theory, the Lagrangian can be written as spatial integral of a Lagrangian density $\mathcal{L}(\phi_i, \partial_\mu \phi_i)$, that is a function of one or more fields ϕ_i and their spacetime derivatives $\partial_\mu \phi_i$. For the action, this yields

$$S = \int L dt = \int \mathcal{L}(\phi_i, \partial_\mu \phi_i) d^4x. \quad (1.1)$$

In the following, the Lagrangian density \mathcal{L} will simply be referred to as the *Lagrangian*.

Using the principle of least action $\delta S = 0$, it and assuming the equation of motions for each field are given by the Euler-Lagrange-equation,

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi_i)} \right) - \frac{\partial \mathcal{L}}{\partial \phi_i} = 0. \quad (1.2)$$

Since all expressions are explicitly Lorentz-invariant, Lagrange formalism is, as opposed to the Hamiltonian formulation, especially well suited for the relativistic dynamics in the SM.

38

Table 1.2: Names, electric charges and masses (rounded to three significant digits if known to that precision) of all observed bosons in the SM [2].

particle	spin	electric charge [e]	mass
photon (γ)	1	0	0
gluon (g)	1	0	0
W^\pm	1	± 1	80.4 GeV
Z^0	1	0	91.2 GeV
Higgs boson (H)	0	0	125 GeV

₁ 1.1.3 Renormalisation

₂ 1.2 Supersymmetry

Chapter 2

1

The LHC and ATLAS

2

Chapter 3

1

Data and Monte Carlo Simulation

2

3.1 Data

3

Chapter 4

1

Statistical data analysis

2

Chapter 5

1

Analysis

2

Chapter 6

1

Summary

2

Here be dragons/

3

Bibliography

- [1] P. J. Mohr, D. B. Newell, and B. N. Taylor, “CODATA Recommended Values of the Fundamental Physical Constants: 2014,” *Rev. Mod. Phys.* **88** no. 3, (2016) 035009, [arXiv:1507.07956 \[physics.atom-ph\]](#).
2
3
4
- [2] C. Patrignani and P. D. Group, “Review of particle physics,” *Chinese Physics C* **40** no. 10, (2016) 100001. <http://stacks.iop.org/1674-1137/40/i=10/a=100001>.
5
6
- [3] **Super-Kamiokande** Collaboration, Y. Fukuda *et al.*, “Evidence for oscillation of atmospheric neutrinos,” *Phys. Rev. Lett.* **81** (1998) 1562–1567, [arXiv:hep-ex/9807003 \[hep-ex\]](#).
7
8
9
- [4] Z. Maki, M. Nakagawa, and S. Sakata, “Remarks on the unified model of elementary particles,” *Prog. Theor. Phys.* **28** (1962) 870–880. [34(1962)].
10
11
- [5] M. Kobayashi and T. Maskawa, “CP Violation in the Renormalizable Theory of Weak Interaction,” *Prog. Theor. Phys.* **49** (1973) 652–657.
12
13
- [6] M. E. Peskin and D. V. Schroeder, *An Introduction to quantum field theory*. Addison-Wesley, Reading, USA, 1995.
14
15
16
<http://www.slac.stanford.edu/~mpeskin/QFT.html>.

Symbols

1

Roman Symbols

2

LEP Large Electron Positron Collider, page 5

3

QED Quantum Electrodynamics, page 5

4

QFT Quantum Field Theory, page 7

5

SM Standard Model of Particle Physics, page 5

6

Acronyms / Abbreviations

7

CKM Cabibbo-Kobayashi-Maskawa, page 6

8

PMNS Pontecorvo–Maki–Nakagawa–Sakata, page 6

9

Appendix A

1

A.1 N-1 plots for cut-scan results

2

Appendix B

1

B.1 Scatter plots comparing truth and reco yields in the SRs

2

3

Acknowledgements

1

An dieser Stelle möchte ich mich herzlich bei allen bedanken, die mich bei der Anfertigung dieser Arbeit unterstützt haben. Insbesondere danke ich herzlich

2

3

- Prof. Dr. Dorothee Schaile für die Möglichkeit, diese Arbeit an ihrem Lehrstuhl durchzuführen sowie das Korrekturlesen der Arbeit.
- Dr. Jeanette Lorenz für die ausgezeichnete Betreuung, die vielen Anregungen, sowie die ehrliche und konstruktive Kritik beim Korrekturlesen dieser Arbeit. Sie hat es mir ermöglicht aktiv im 1-Lepton Analyseteam an der Suche nach Supersymmetrie mitwirken zu können.
- Dr. Nikolai Hartmann für die unzähligen Diskussionen über den Sinn und Unsinn der Datenanalyse mit und ohne ATLAS Software. Vielen Dank für die stets geduldige und ausführliche Beantwortung meiner Fragen, sowie das Bereitstellen unzähliger Zeilen Code, ohne die vieles schwieriger gewesen wäre.
- Allen Mitgliedern des Lehrstuhls Schaile für die angenehme und freundliche Arbeitsatmosphäre.
- Allen Freunden, die stets da waren, wenn ich sie gebraucht habe.

4

5

6

7

8

9

10

11

12

13

14

15

16

I also want to thank the entire 1-lepton analysis team, especially the coordinators Jeanette Lorenz, Da Xu and Alberto Cervelli. Thank you for the always supportive and enjoyable work environment. Many thanks also to Valentina Tudorache for patiently answering all my questions as well as all the entertaining conversations.

17

18

19

20

I would further like to thank Dr. Brian Petersen without whom the presented pMSSM studies would not have been possible.

21

22

En léiwen Merci och dem Yannick Erpelding fir d’Korrekturliesen—och wann en net alles verstanen huet—an dem Nick Beffort, fir all déi domm Reddit Posts, d’Korrekturliesen, an dei onzähleg Stonnen zesummen mat enger Spezi an der Hand.

23

24

25

Zu gudder Läscht, wëll ech op dëser Platz menger ganzer Famill merci soen, virun allem mengen léiwen Elteren an menger wonnerbarer Schwëster. Merci dass dir mëch bei allem waat ech maachen ënnerstëtzt an dass ech ëmmer op iech zielen kann, och wann ech weit fort sin. Ouni iech wier daat heiten net méiglech gewiescht. Besonneschen Merci och dem Nathalie Münster, dofir dass et mech seit Joren ëmmer ënnerstëtzt an ëmmer fir mech do as, och wann ech heiansdo depriméiert oder duercherneen sin.

26

27

28

29

30

31

Selbstständigkeitserklärung

1

Hiermit erkläre ich, die vorliegende Arbeit mit dem Titel

2

WIP: Work in Progress Title

3

WIP: Work in Progress Title

4

selbständig verfasst zu haben und keine anderen als die in der Arbeit angegebenen
Quellen und Hilfsmittel benutzt zu haben.

5

6

Eric Schanet

7

München, den 01. Mai 2021

8