The first measurement of the differential cross-sections for the electroweak production of ZZ in association with two jets in the four-leptons final state in 13 TeV proton-proton collision with the ATLAS detector.

A Dissertation

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The Faculty of the Graduate School of Arts and Sciences
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Department of Physics

Professor Gabriella Sciolla, Advisor

In Partial Fulfillment
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by
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ABSTRACT

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A dissertation presented to the Faculty of the
Graduate School of Arts and Sciences of Brandeis University
Waltham, Massachusetts

By Prajita Bhattarai

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- H: Weak Hypercharge

- I: Weak Isospin

- LH: Left Handed

- Q: Electric Charge

- RH: RightHanded

- SM: Standard Model

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Chapter I: **Introduction**

Chapter II: Theory

This chapter describes the theoretical framework of the experimental measurements discussed in this thesis. The Standard Model (SM) of particle physics is introduced and concepts relevant to the thesis are discussed in Section 1. Section 2 discusses the outstanding problems with the Standard Model thus, motivating the experimental measurement. Finally, Section 3 discusses the phenomenology of the proton-proton collisions relevant in context of the electroweak di-Zboson measurement.

1 The Standard Model

1.1 Overview

The Standard Model (SM) of particle physics is a mathematical framework based on quantum field theory which incorporates quantum mechanics and special relativity and describes the known fundamental particles in nature and all their interactions. It consists of two sets of particles with intrinsic angular momentum, half-integer-spin fermions which are fundamental constituents of matter particles, and force-carrying integer-spin bosons. The seventeen fundamental particles of the SM and their properties such as mass, charge, and intrinsic spin are shown schematically by figure 1. Discussion in this section is written with the guidance from [3].
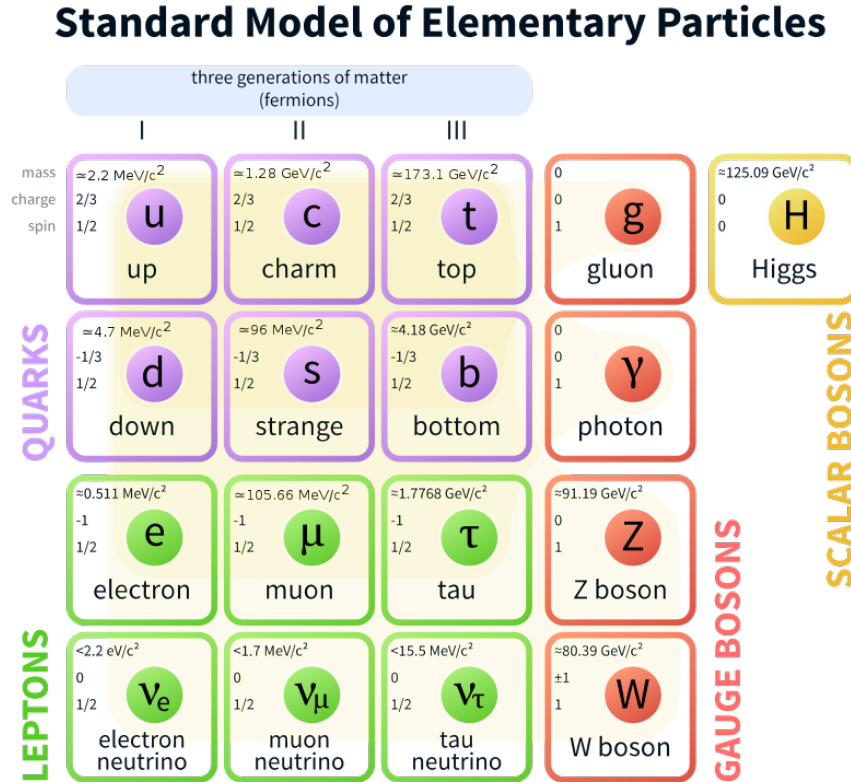

Figure 1: The seventeen fundamental particles of the Standard Model include three generations of twelve fermions, four gauge bosons, and the scalar Higgs bosons. [2]

Table 1: Properties of Standard Model gauge bosons. [1]

Interaction Type		Particle	Q	Mass $[GeV]$	Symmetry Group
Electroweak	Electromagnetic	Photon (γ)	0	0	$SU(2) \otimes U(1)$
	Weak	$W^{\pm}$	± 1	80.4	
		Z boson	0	91.2	
Strong		gluons (g)	0	0	$SU(3)$

The twelve half-integer-spin fermions can be further distinguished into two categories, leptons, and quarks, each having three generations of particles with similar properties as shown schematically by figure 1. For each fermion, there exists an anti-fermion with the same additive quantum numbers but with opposite signs. The four spin 1 bosons shown in Table 1 are collectively called the gauge bosons. The quanta of these gauge fields mediate the electromagnetic, weak, and strong interactions. Gauge fields are invariant under various local group transformations that preserve some quantum numbers associated with the interactions and are discussed in detail in Section 1.2 [4].Different fermions take part in different interactions as outlined by Table 2, and the strength of the interaction is governed by a gauge coupling parameter.

Massless photon (γ) mediates the electromagnetic interaction. The massive W and Z bosons mediate weak interaction. The Standard Model unifies electromagnetic and weak forces to a unified electroweak theory which follows from $SU(2)_L \otimes U(1)_Y$ gauge symmetry discussed in detail in Section 1.2.3. Weak isospin (I) and weak hypercharge (Y) are the quantum numbers associated with the $SU(2)_L$ and $U(1)_Y$ gauge groups respectively. The electric charge (Q) which is conserved in all interactions is related to the isospin and hypercharge by $Q = I_3 + \frac{Y}{2}$, where I_3 is the third component of the weak isospin. The $SU(2)_L$ group follows a chiral structure where the gauge fields couple explicitly to the left-handed (LH) chiral fermions states and the right-handed (RH) chiral anti-fermions states. Thus, each generation of fermion contains a left-handed doublet with $I = \frac{1}{2}$ and a right-handed singlet carrying $I = 0$ which are shown in Table 3.

Table 2: Summary of different interactions of fermions under different gauge theory. The check mark suggest that the fermions interact via associated force.

Particles		Strong $SU(S)$	Electromagnetic $U(1)$	Weak $SU(2)$
Quarks	u, c, t d, s, b	✓	✓	✓
Leptons	e, μ, τ	-	✓	✓
	ν_e, ν_μ, ν_τ	-	✓	-

Each generation of lepton, electron (e), muon (μ) and tau (τ) is accompanied by a neutral particle called neutrino (ν) with same lepton flavor ($\nu_e, \nu_\mu \& \nu_\tau$). The lepton flavor is conserved by the Standard Model. Standard Model neutrinos are their own anti-particles and only left-handed neutrinos are predicted by the theory.

The quarks can be further categorized into two categories, the up-type quarks with $+\frac{2}{3}$ charge and the down-type quarks with $-\frac{1}{3}$ charge. Up (u), charm (c) , & top (t) are the first, second, and third generation of the up-type quarks, while the down (d), strange (s) & bottom (b) are the three generations of the down-type quarks. The down-type left-handed quarks in $SU(2)_L$ quark doublets $d', s' \& b'$ summarized in table 3 are linear combinations of d, s, b quarks. The quarks interact strongly with one another by strong interaction mediated by the massless neutral gluons which follow from $SU(3)$ gauge symmetry by exchange of color charges. Each quark can have either one of the three color charges (red, blue &, green), whereas an anti-quark can have either anti-red, anti-blue, or anti-green color charge. There are eight gluons in the Standard Model with color charges formed by a combination of either of the two color charges. Since gluons have a color charge, they interact with other gluons strongly.

Higgs boson is the only spin-0 scalar particle in the theory with no charge and gives masses to all other particles through Spontaneous Symmetry Breaking which will be discussed in section 1.2.3.

Table 3: Electroweak quantum numbers of Standard Model half-integer spin fermions (quarks and leptons) arranged in a left-handed $SU(2)$ doublet and right-handed $SU(2)$ singlet. [3]

Particle Types	First	Second	Third	I_3	Y	Q
Leptons	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$-\frac{1}{2}$ $\frac{1}{2}$	-1 -1	-1 0
	e_R	μ_R	τ_R	0	-2	-1
Quarks	$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	$\frac{1}{2}$ $-\frac{1}{2}$	$\frac{1}{3}$ $\frac{1}{3}$	$\frac{2}{3}$ $-\frac{1}{3}$
	u_R	c_R	t_R	0	$\frac{4}{3}$	$\frac{2}{3}$
	d_R	s_R	b_R	0	$-\frac{2}{3}$	$-\frac{1}{3}$

1.2 Theoretical Formulation

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1.2.2 Quantum Chromodynamics

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Appendix

A Contribution