

Constraints on Anomalous Quartic Gauge Couplings in the Electroweak Gauge Boson Scattering WZjj Final State with the ATLAS Detector

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Tobias Sandmann

geboren am 11.10.1988 in Finsterwalde

TECHNISCHE UNIVERSITÄT DRESDEN

INSTITUT FÜR KERN- UND TEILCHENPHYSIK

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1. Gutachter: Prof. Dr. Michael Kobel
2. Gutachter: Prof. Dr. Kai Zuber

Kurzdarstellung

Diese Arbeit befasst sich mit dem Endzustand $W^\pm Zjj$ der elektroschwachen Eichbosonenstreuung, mit Hilfe dessen die anomalen quartischen electroschwachen Eichkopplungen α_4 und α_5 eingeschränkt werden sollen. Diese Kopplungen werden im Zuge einer effektiven Feldtheorie eingeführt, sie parametrisieren Niedrigenergie-Effekte von möglichen Theorien jenseits des Standardmodells der Teilchenphysik auf modellunabhängige Weise. Effektive Feldtheorien werden eingeführt, weil vermutet wird, dass es sich beim Standardmodell nur um einen Niedrig-Energie-Limes einer noch unbekannten Theorie handelt.

Für die Analyse in dieser Arbeit wurden die vom ATLAS Detektor aufgezeichneten Daten von Proton-Proton-Kollisionen mit einer Schwerpunktsenergie von $\sqrt{s} = 8 \text{ TeV}$ und einer integrierten Luminosität von $\int \mathcal{L} dt = 20.281 \text{ fb}^{-1}$ aus dem Jahr 2012 verwendet.

Die erwarteten eindimensionalen oberen Grenzen wurden für eine optimierte Ereignisauswahl auf 0.29 für α_4 und 0.30 für α_5 mit einem Vertrauensniveau von 95% bestimmt. Die beobachteten Grenzen für die gleiche Ereignisauswahl sind weniger restriktiv, weil es einen Überschuss in den Daten gibt, sie betragen 0.53 für α_4 und 0.52 für α_5 .

Abstract

This work analyses the electroweak gauge boson scattering final state $W^\pm Zjj$ to constrain the anomalous quartic electroweak gauge couplings α_4 and α_5 . They are introduced within an effective field theory ansatz and parametrize low energy effects of possible theories beyond the Standard Model of particle physics in a model independent manner. This is done, because it is assumed that the Standard Model is a low energy approximation of a so far unknown theory.

The analysis is performed with the recorded ATLAS data from proton-proton collisions in 2012 with a center-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$ and an integrated luminosity of $\int \mathcal{L} dt = 20.281 \text{ fb}^{-1}$.

Expected one-dimensional upper limits at 95% confidence level for α_4 and α_5 are determined for an optimized event selection to 0.29 for α_4 and 0.30 for α_5 . The observed constraints for the same selection are less restrictive due to an excess in data, they amount to 0.53 for α_4 and 0.52 for α_5 .

Contents

1	Introduction	1
2	Theoretical Foundations	3
2.1	The Standard Model of Particle Physics	3
2.1.1	Overview	3
2.1.2	Electroweak Gauge Theory	6
2.1.3	Electroweak Symmetry Breaking	8
2.2	Anomalous Quartic Electroweak Gauge Boson Interactions	10
2.2.1	Effective Field Theories	11
2.2.2	Effective Theory of Electroweak Interactions	12
2.2.3	Anomalous Quartic Gauge Couplings	15
2.2.4	K-Matrix Unitarization	15
3	Experimental Setup	17
3.1	Large Hadron Collider	17
3.2	The ATLAS Experiment	19
3.2.1	Coordinate System	20
3.2.2	Inner Detector	21
3.2.3	Calorimeter System	23
3.2.4	Muon Spectrometer	25
3.2.5	Trigger System	26
3.2.6	Luminosity Measurement	26
3.2.7	Data Quality	27
4	Electroweak Gauge Boson Scattering	29
4.1	Definition	29
4.2	$W^\pm Zjj$ Gauge Boson Scattering	30
4.3	Background Processes for $W^\pm Zjj$ -EW	32
5	Object Reconstruction and Signal Event Selection	35
5.1	Object Reconstruction and Selection	35
5.1.1	Trigger	35
5.1.2	Primary Vertex	35
5.1.3	Electrons	36
5.1.4	Muons	36

5.1.5	Jets	36
5.1.6	Missing Momentum	37
5.2	Signal Event Selection	37
6	Event Simulation	39
6.1	Event Simulation Chain	39
6.2	Simulation Corrections	41
6.3	The Event Generator WHIZARD	42
6.4	Signal Event Generation	42
6.4.1	Generation Phase Space	43
6.4.2	Samples for Anomalous Quartic Gauge Couplings	43
6.4.3	Next-to-Leading Order Corrections	44
7	Constraints on Anomalous Quartic Electroweak Gauge Couplings	47
7.1	Statistical Method	47
7.2	Systematic Uncertainties	50
7.3	aQGC Sensitive Variables	52
7.4	Optimization	53
8	Conclusion	59
A	Mathematical Utilities	61
A.1	Pauli and Dirac Matrices	61
A.2	Chirality Projection	62
B	Monte Carlo Samples and Recorded Data	63
	List of Figures	65
	List of Tables	67
	Bibliography	69

1 Introduction

The Standard Model of particle physics (SM) is the theoretical foundation for the description of fundamental particles but despite its great success with that and the extremely good agreement to the measurements the SM has its weaknesses and there are phenomena it can not explain. For that reason, the SM is supposed to be a low energy approximation of a still unknown more complex theory, whose internal structure is hidden at currently accessible energies. But it is possible, that low energy effects of such a theory are already observable in modified coupling constants. Therefore, in this work an effective field theory is used to introduce anomalous quartic electroweak gauge couplings and investigate whether there are observable deviations from the SM prediction for the four gauge boson vertex in the scattering of a W boson with a Z boson. The advantage of effective field theories is that they are able to parametrize such low energy effects without deciding for a certain theory.

This work is structured in the following manner: Initially the theoretical foundations are introduced in Chapter 2, that includes the SM with the focus on the electroweak gauge theory as well as effective field theories. In Chapter 3 the Large Hadron Collider and the ATLAS detector are described. Chapter 4 elaborates on electroweak gauge boson scattering and background processes which have or mimic the same detector signature. In Chapter 5 and 6 the reconstruction and simulation of events are elucidated. The subsequent chapter 7 is dedicated to the constraining of anomalous quartic electroweak gauge couplings. Finally, in Chapter 8 the results are summarized and discussed.

2 Theoretical Foundations

2.1 The Standard Model of Particle Physics

This chapter gives a brief introduction to the Standard Model of particle physics (SM) [1,2] and describes some of its implications. The SM is an extremely successful theory, describing all known fundamental particles and their interactions in excellent agreement with data from experimental measurements. The emphasis of this thesis will be on the electroweak gauge theory, which is part of the SM, because it is the foundation for interactions of electroweak gauge bosons which are central to this work.

2.1.1 Overview

Mathematically, the SM is a renormalizable relativistic quantum field theory with a local $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry. Except for gravitation the SM incorporates all known fundamental interactions: strong, weak and electromagnetic. The strong interaction is described by the $SU(3)_c$ symmetry with c denoting the strong charge “color”. $SU(2)_L \otimes U(1)_Y$ is the symmetry group of the electroweak interaction, which is the unification of weak and electromagnetic interactions. The indices L and Y are denoting the *left chirality*, due to the fact that only left-handed fields transform under this group, and the *weak hypercharge* Y , respectively. The symmetry group of the electromagnetic interaction $U(1)_{em}$ is a subgroup of the $SU(2)_L \otimes U(1)_Y$. The gauge principle for gauge theories demands, that the number of generators of a symmetry group is equal to the number of associated gauge fields [3]. Elementary particles are described as excitations of quantum fields and interactions between them are introduced by the demand for gauge invariance. The particle content of the SM can be subdivided into two categories dependent on the spin: *fermions* and *bosons*.

Fermions

Fermions have a spin of $(n + 1/2)$ for $(n \in \mathbb{N}_0)$ and are characterized by *Fermi-Dirac statistics*. All elementary fermions in the SM have a spin of $1/2$. They can be further subdivided into *leptons* and *quarks*.

The **leptons** can either have an electric charge of ± 1 or 0 . There are 6 charged leptons: the electron e^- , the muon μ^- , the tau τ^- and their corresponding anti-particles with the same properties but opposite charge: the positron e^+ , the antimuon

μ^+ and the antitau τ^+ . Similarly, the SM includes 6 chargeless leptons referred to as *neutrinos*: the electron neutrino ν_e , the muon neutrino ν_μ , the tau neutrino as well as their anti-particles: $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$.

Quarks have an electric charge of either $\pm 1/3$ or $\pm 2/3$. There are 6 types of quarks¹: up u , down d , charm c , strange s , top t and bottom b and 6 types of antiquarks: $\bar{u}, \bar{d}, \bar{c}, \bar{s}, \bar{t},$ and $\bar{b}$ with the same names like the quarks plus the prefix “anti-”. They have again the same properties as their corresponding quarks but opposite charges. u, c and t are referred to as *up-type* quarks, while d, s and b are known as *down-type* quarks. Quarks have an additional charge: the color c , which is as already mentioned the charge of the strong interaction. There are 3 different colors, thus every flavour has 3 representatives resulting in a total number of 18 different quarks and 18 different antiquarks with the corresponding anticolors. In nature no color charges are observed, therefore quarks can only exist in bound states, this fact is called *confinement* [4].

The fermions can be grouped into 3 generations, each generation consists of a charged lepton, its corresponding neutrino and two quarks, one up-type and one down-type quark and all corresponding anti-particles. The generations are listed in Table 2.1 together with their electric charges and masses. The fermions in one generation show the same behaviour under symmetry transformations as their counterparts in the other generations, only the masses are different.

Table 2.1: Fermions of the Standard Model with electric charges and masses [5].

Generation	Fermion	Electric charge	Mass [MeV] ²
1 st	e^- electron	-1	0.511
	ν_e electron neutrino	0	$< 2 \times 10^{-6}$ (95% CL) ³
	u up	2/3	$2.3^{+0.7}_{-0.5}$ ($\overline{\text{MS}}, \mu = 2 \text{ GeV}$) ⁴
	d down	-1/3	$4.8^{+0.5}_{-0.3}$ ($\overline{\text{MS}}, \mu = 2 \text{ GeV}$)
2 nd	μ^- muon	-1	105.658
	ν_μ muon neutrino	0	< 0.19 (90% CL)
	c charm	2/3	1275 ± 0.025 ($\overline{\text{MS}}, \mu = m_c$) ⁵
	s strange	-1/3	95 ± 5 ($\overline{\text{MS}}, \mu = 2 \text{ GeV}$)
3 rd	τ^- tau	-1	1776.82 ± 0.16
	ν_τ tau neutrino	0	< 18.2 (95% CL)
	t top	2/3	$(173.21^{+0.51}_{-0.71}) \times 10^3$
	b bottom	-1/3	4180 ± 30 ($\overline{\text{MS}}, \mu = \bar{m}_b$) ⁵

¹They are also referred to as quark *flavours*.

²In particle physics usually “natural” units are used: $\hbar = c = e = 1$.

³The *confidence level* CL gives the probability for a measured interval to cover the true value.

⁴Quark masses depend on the chosen renormalization scheme and renormalization scale μ , here

Bosons

Bosons generally have a spin of n for ($n \in \mathbb{N}_0$) and obey the *Bose-Einstein statistics*. The SM contains bosons with spin 0 and 1. The bosons with spin 1 are the photon γ , 8 gluons g , W^+ , W^- and Z . They behave like 4-vectors under Lorentz transformations and are called vector bosons for that reason. In addition, they have a second name: *gauge bosons* referring to the fact, that they are introduced to the theoretical framework of the SM to ensure local gauge invariance. They are the mediators of the different interactions. The photon is the gauge boson of the electromagnetic interaction and couples to all electrically charged particles. Electromagnetic interactions are described by quantum electrodynamics (QED) [6–8]. Gluons are the mediators of strong interactions and couple only to quarks and other gluons, because these are the only color charged particles. The theory describing strong interactions is quantum chromodynamics (QCD) [9–12]. $W^\pm$ and Z couple to all left-handed fermions as the mediators for the weak interaction. They are the only massive gauge bosons, which will be explained in Section 2.1.3. Weak interactions can only be fully described in the framework of the unification of weak and electromagnetic interaction, called the electroweak gauge theory also known as Glashow-Weinberg-Salam (GWS) theory [1, 2, 13].

The Higgs boson has a spin of zero [14], it is also referred to as a *scalar* boson, because of its invariance under arbitrary Lorentz transformations. Unlike the gauge bosons it is not the mediator of a force but couples to all massive particles. It emerges from the *electroweak symmetry breaking*, which is covered in Section 2.1.3. Table 2.2 provides an overview of the bosons and their masses.

Table 2.2: Bosons of the Standard Model, the interactions they mediate, their experimental masses, electric charges and spins [5].

Boson		Interaction	Mass [GeV]	Electric charge	Spin
photon	γ	electromagnetic	$< 1 \times 10^{-18}$	0	1
W bosons	$W^\pm$	weak	80.385 ± 0.015	± 1	1
Z boson	Z	weak	91.1876 ± 0.0021	0	1
gluons	g	strong	0 ⁶	0	1
Higgs	H		125.7 ± 0.4	0	0

the modified minimal subtraction scheme $\overline{\text{MS}}$ is used and $\mu = 2 \text{ GeV}$.

⁵Here the renormalization scale is the “running” mass.

⁶This value arises from theory. A mass of at least some MeV can not be precluded [3].

2.1.2 Electroweak Gauge Theory

The electroweak gauge theory is of particular interest to this work, because it contains the interactions of fermions with electroweak gauge bosons as well as the gauge boson self-interactions. The theory has been developed by Abdus Salam, Sheldon Glashow and Steven Weinberg [1, 2, 13] in the 1960s. It unifies electromagnetic and weak interactions and is based on the $SU(2)_L \otimes U(1)_Y$ gauge group, meaning it has to be invariant under transformations of this group. The central element of a quantum field theory is the Lagrangian density, it can be written in the following form^{7 10}:

$$\begin{aligned} \mathcal{L}_{\text{ew}} = & + i \bar{L}_L^j \gamma^\mu D_\mu L_L^j + i \bar{l}_R^j \gamma^\mu D_\mu l_R^j \\ & + i \bar{Q}_L^j \gamma^\mu D_\mu Q_L^j + i \bar{u}_R^j \gamma^\mu D_\mu u_R^j + i \bar{d}_R^j \gamma^\mu D_\mu d_R^j \\ & - \frac{1}{4} W_{a,\mu\nu} W_a^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}. \end{aligned} \quad (2.1)$$

The first line contains the lepton terms, the second the quark terms and the third the terms of the gauge fields. The indices R/L indicate the chirality of the fields. Using the projection operators⁸

$$P_{R/L} = \frac{1}{2} (\mathbb{1}_4 \pm \gamma^5), \quad (2.2)$$

a fermion field ψ ⁹ can be split into its right and left-handed components $\psi_{R/L}$ (see also Appendix A.2). For the left-handed fields a doublet notation is used, while the right-handed fields are singlets. Table 2.3 gives an overview of the fermion fields. The bar over a fermion field, denotes the adjoint field, defined as

$$\bar{\psi} = \psi^\dagger \gamma^0. \quad (2.3)$$

γ^μ ($\mu = 0, 1, 2, 3$) and γ^5 are 4×4 Dirac matrices with $\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$ (for more information see Appendix A.1) and D_μ is the covariant derivative, which replaces the simple partial derivative ∂_μ to ensure local gauge invariance for the transformation of a fermion field ψ :

$$\psi \rightarrow \psi' = e^{iY\alpha(x^\mu)} e^{iT_a\beta^a(x^\mu)} \psi \quad (2.4)$$

⁷The index j denotes the generation and is used to shorten the expression, the terms have to be added for each generation ($j = 1, 2, 3$). “i” is the imaginary unit with $\sqrt{-1} = -1$.

⁸The expression $\mathbb{1}_4$ indicates the 4×4 identity matrix.

⁹ ψ is used as the representative for all the different fermion fields.

by introducing the gauge fields W_μ^a ($a = 1, 2, 3$) and B_μ . D_μ can be expressed as¹⁰:

$$D_\mu = \partial_\mu + ig_W T_a W_\mu^a + ig_Y Y B_\mu \quad (2.5)$$

with the gauge couplings g_Y and g_W and the generators $T_a = \sigma_a/2$ of the $SU(2)_L$ and Y of the $U(1)_Y$. σ_a are the 2×2 *Pauli matrices* (see also Appendix A.1).

Table 2.3: Fermion doublet and singlet fields of the SM. The left-handed fields are arranged in doublets, while the right-handed fields use a singlet notation, reflecting the fact, that only left-handed fields transform under the electroweak gauge group. Also shown are the electric charge $Q = T_3 + Y$, the weak hypercharge Y and the third component of the weak isospin T_3 . j denotes the generation.

Leptons	$j = 1$	$j = 2$	$j = 3$	Y	Q	T_3
L_L^j	$\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu,L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau,L} \\ \tau_L \end{pmatrix}$	$-1/2$	0	$+1/2$
l_R^j	e_R	μ_R	τ_R	-1	-1	0
Quarks	$j = 1$	$j = 2$	$j = 3$	Y	Q	T_3
Q_L^j	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	$+1/6$	$+2/3$	$+1/2$
u_R^j	u_R	c_R	t_R	$+2/3$	$+2/3$	0
d_R^j	d_R	s_R	b_R	$-1/3$	$-1/3$	0

The last part of the Lagrangian in Equation 2.1 are the gauge field terms which consist of the field strength tensors $W_a^{\mu\nu}$ and $B^{\mu\nu}$. They are defined as:

$$W_a^{\mu\nu} = \partial^\mu W_a^\nu - \partial^\nu W_a^\mu - g_W \varepsilon_{abc} W_b^\mu W_c^\nu \quad (2.6)$$

$$B^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu \quad (2.7)$$

and determine the kinematics of the gauge fields and introduce self-interaction terms for the non-abelian group $SU(2)_L$.

The physical fields of the $W^\pm$ bosons are a linear combination of W_1^μ and W_2^μ :

$$W^{\pm\mu} = \frac{1}{\sqrt{2}} (W_1^\mu \mp i W_2^\mu) \quad (2.8)$$

Neither W_3^μ nor B^μ can be associated with the photon field A^μ , because both couple

¹⁰Throughout this chapter the *Einstein summation convention* is used, i.e. summation over identical upper and lower indices.

to the neutrino fields. For that reason A^μ and Z^μ must be linear combinations of W_3^μ and B^μ :

$$\begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix} = \begin{pmatrix} \cos \vartheta_W & \sin \vartheta_W \\ -\sin \vartheta_W & \cos \vartheta_W \end{pmatrix} \begin{pmatrix} B^\mu \\ W_3^\mu \end{pmatrix} \quad (2.9)$$

with the *electroweak mixing angle* ϑ_W , which has to be chosen in a manner, that A^μ does not couple to the neutrino fields. This implies:

$$\frac{\sin \vartheta_W}{\cos \vartheta_W} = \frac{g_Y}{g_W}. \quad (2.10)$$

The second requirement, demanding that A^μ couples to the fermion fields like in QED, relates the charge Q to Y and T_3 and the electromagnetic coupling constant e to the electroweak coupling constants g_W and g_Y :

$$Q = Y + T_3 \quad (2.11)$$

$$e = g_W \sin \vartheta_W = g_Y \cos \vartheta_W. \quad (2.12)$$

Up to this point all fields are massless, because mass terms like:

$$\mathcal{L}_{m_f} \sim m_f \bar{\psi} \psi = m_f (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L) \quad (2.13)$$

$$\mathcal{L}_{M_Z} \sim M_Z^2 Z^\mu Z_\mu \quad (2.14)$$

are not gauge invariant and therefore not included in the Lagrangian. However, the results of experiments in particle physics show clearly, that fermions and bosons are massive¹¹ and the solution for this discrepancy is provided by the electroweak symmetry breaking mechanism.

2.1.3 Electroweak Symmetry Breaking

The electroweak symmetry breaking is achieved through the BEH mechanism [15,16], named after its discoverers Brout, Englert and Higgs. It introduces a complex scalar isodoublet field

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} \quad (2.15)$$

which has a hypercharge of $Y = 1/2$ and is invariant under $SU(2) \otimes U(1)$ transformations. The electroweak Lagrangian in Equation 2.1 is extended by the Lagrangian of

¹¹Except for photons and gluons.

a complex scalar field:

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi). \quad (2.16)$$

Here the covariant derivative D_μ is defined accordingly to Equation 2.5. The potential $V(\Phi)$, constrained by the demand for gauge invariance and renormalisability, has the form:

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2. \quad (2.17)$$

with the two real parameters $\mu, \lambda > 0$. It has an infinite number of non-zero minima at

$$|\Phi_0| = \sqrt{\frac{\mu^2}{2\lambda}} = \frac{v}{\sqrt{2}} \quad (2.18)$$

with the *vacuum expectation value* $v \approx 246$ GeV, whose value is known due to precise measurements of the muon decay width [5]. One of the minima is chosen to represent the ground state¹²:

$$\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}. \quad (2.19)$$

This special choice breaks the electroweak gauge symmetry $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{\text{em}}$, because Φ_0 is not gauge invariant, but conserves the electromagnetic gauge symmetry, due to the choice of the charged scalar field $\Phi^+ = 0$.

An expansion around the ground state can be parametrized in the following way:

$$\Phi(x) = \begin{pmatrix} g_1(x) + i g_2(x) \\ \frac{1}{\sqrt{2}}(v + h(x)) + i g_3(x) \end{pmatrix} \quad (2.20)$$

with the real scalar fields h and $g_i (i = 1, 2, 3)$. The g_i are associated to Goldstone bosons, which are created when a continuous symmetry is spontaneously broken [17]. The Goldstone bosons are unphysical and vanish when a special gauge transformation is applied. Their degrees of freedom are absorbed by the weak gauge bosons $W^\pm$ and Z , which thereby becoming massive. The remaining field h is related to the massive Higgs boson, which is an excitation of the Higgs field. Hence, Φ has the form:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}. \quad (2.21)$$

¹²Through gauge transformations it is possible to transform into every other minimum.

Inserting it into Equation 2.16 yields the masses of the gauge bosons:

$$\begin{aligned} M_W &= \frac{1}{2}vg_W \\ M_Z &= \frac{1}{2}v\sqrt{g_W^2 + g_Y^2} \\ M_A &= 0 \end{aligned} \tag{2.22}$$

as well as the interactions between the Higgs field and the gauge fields.

The fermions are still massless and their masses are not predicted by this theory. The mass terms have to be inserted by hand, therefore the Lagrangian in Equation 2.16 has to be extended once again by the *Yukawa* Lagrangian¹³

$$\mathcal{L}_Y = y_l^j \bar{L}_L^j \Phi l_R^j + y_u^j \bar{Q}_L^j \Phi^C u_R^j + y_d^j \bar{Q}_L^j \Phi d_R^j + h.c. \tag{2.23}$$

thus the mass of fermion f has the value $m_f = y_f v / \sqrt{2}$. The y_f are Yukawa couplings, which have to be chosen in a manner, that the m_f are identical to the experimentally measured masses. Neutrinos remain massless in the the SM, as it is not clear how to implement mass terms, due to the absence of righthanded neutrino singlets. But they are massive, because neutrino oscillation has been observed, which is possible because the neutrino mass eigenstates do not match to electroweak eigenstates.

2.2 Anomalous Quartic Electroweak Gauge Boson Interactions

At the moment the SM is in very good agreement with measurements at accessible energies, but the theory still has weaknesses, some examples are:

- The Yukawa couplings are not derived from first principles and hence the masses are not given by an underlying principle.
- The SM has a hierarchy problem [18].
- The strong and the electroweak interaction are not unified and the gravitational interaction is not even included.
- There are no dark matter candidates.

There exist plenty of new theories describing physics beyond the Standard Model (BSM), but usually consequent phenomena occur at not yet accessible interaction energies. These phenomena can still have observable effects in the accessible region and a possibility to parametrize such effects without deciding for a particular theory

¹³ Φ^C is the charge conjugated scalar field, defined as $\Phi^C = i\sigma_2\Phi$ with the Pauli matrix σ_2 .

are *effective field theories*, which are introduced in Section 2.2.1. This work focuses on quartic electroweak gauge boson interactions and in Section 2.2.2 is described how to use an effective theory for parametrizing possible BSM effects, which manifest in *anomalous* quartic gauge couplings (aQGCs).

2.2.1 Effective Field Theories

The choice of a special model describing new physics at so far inaccessible energies is pointless because of the lack of knowledge about phenomena in that region. Effective field theories (EFTs) are a model-independent way for parametrizing low energy effects of new theories, which are already observable in modified interactions between the known particles at accessible energies. Therefore it is necessary that an EFT contains the symmetries and assumptions of the established underlying low energy theory. EFTs are *non-renormalizable* due to an infinite number of parameters, representing implicitly the infinite number of possible new theories and they are also only valid up to an energy scale Λ where the microscopic structure of a new theory starts becoming non-negligible. The most popular example for an EFT is the Fermi theory of weak interactions, which is described in the next paragraph.

Fermi Theory of Weak Interactions

When the weak gauge bosons $W^\pm$ and Z were still unknown, Enrico Fermi developed an effective theory to explain the beta decay [19], which is also applicable to the muon decay into 3 leptons $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$. The 4 involved leptons interact in one vertex (see Figure 2.1a). The effective Lagrangian of the Fermi theory is:

$$\mathcal{L}_{\text{Fermi}} = -\frac{G_F}{\sqrt{2}} \bar{\nu}_\mu \gamma^\alpha (1 - \gamma^5) \mu \bar{e} \gamma_\alpha (1 - \gamma^5) \nu_e \quad (2.24)$$

with the Fermi constant G_F defined as:

$$\frac{G_F}{\sqrt{2}} = \frac{1}{\Lambda_F^2}. \quad (2.25)$$

Here, Λ_F is the Fermi scale up to which the effective theory is valid. Through the measurement of the muon mass and lifetime those two parameters can be determined to [5]:

$$G_F = 1.1663783(6) \times 10^{-5} \text{ GeV}^{-2} \quad (2.26)$$

$$\Lambda_F \approx 350 \text{ GeV} \quad (2.27)$$

For energies above Λ_F the theory is no longer renormalisable, because with increasing center-of-mass energy $\sqrt{s}$ also the cross section increases without saturation. To

prevent this, one has to use the electroweak theory introduced in Section 2.1.2 with the Lagrangian:

$$\mathcal{L}_{\text{ew}} = -\frac{g_W^2}{8} \bar{\nu}_\mu \gamma^\alpha (1 - \gamma^5) \mu \frac{1}{q^2 - M_W^2} \bar{e} \gamma_\alpha (1 - \gamma^5) \nu_e, \quad (2.28)$$

with an additional propagator term for the exchanged W boson (see Figure 2.1b), which suppresses the increase of the cross section by the momentum transfer $q^2 = s$ and makes it finite. For low energies is $q^2 \ll M_W^2$ and the propagator can be expanded:

$$\frac{1}{q^2 - M_W^2} = -\frac{1}{M_W^2} + \mathcal{O}\left(\frac{q^2}{M_W^2}\right). \quad (2.29)$$

Thus, in lowest order perturbation theory and when using:

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8M_W^2} \quad (2.30)$$

Fermi and electroweak theory are equivalent up to corrections in the order of q^2/M_W^2 .

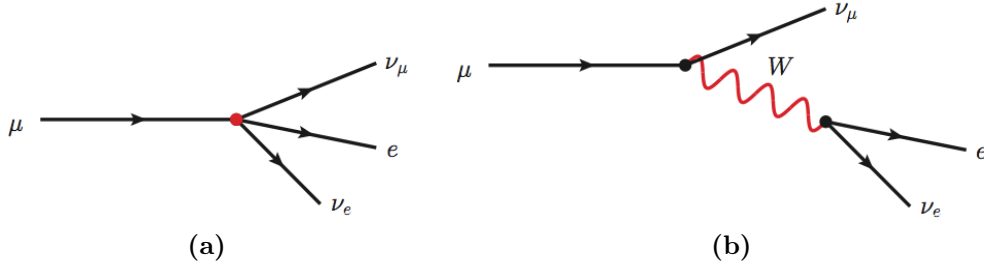


Figure 2.1: Feynman diagrams of the muon decay in: (a) the Fermi theory, (b) the Standard Model at lowest order.

2.2.2 Effective Theory of Electroweak Interactions

The most general extension of the electroweak theory to an effective theory for new physics beyond an energy scale Λ can be written as:

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d \geq 4} \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} \quad (2.31)$$

with the SM Lagrangian $\mathcal{L}_{\text{SM}}$, a sum over the operator dimension d and a sum over all i possible operators $\mathcal{O}_i^{(d)}$ with the same dimension d . Because of the requirement for

baryon and lepton number conservation only operators $\mathcal{O}$ with even dimensions d are allowed. The contributions of the new Operators are suppressed by the scale Λ , the higher the dimension the stronger the suppression [20]. The $\alpha_i^{(d)}$ are dimensionless free coupling parameters, which have to be constrained through measurements.

In this work the anomalous quartic electroweak gauge boson couplings α_4 and α_5 are investigated. They are associated with operators of dimension $d = 4$, which are introduced through an effective theory of electroweak interactions with an so called *chiral* Lagrangian. This Lagrangian is briefly described in the following paragraph.

Electroweak Chiral Lagrangian

The chiral Lagrangian $\mathcal{L}_{\text{chiral}}$ was proposed before the discovery of a Higgs boson. Therefore it covers both cases, the Higgsless as well as the Higgs case. The Higgs field Φ is replaced by the field Σ , which realizes the electroweak symmetry breaking and allows to introduce gauge invariant mass terms for fermions and gauge bosons. This new field is a isospin 2×2 matrix and transforms under $\text{SU}(2)_L$ transformations $U(x)$ and under $\text{U}(1)_Y$ transformations $V(x)$ in the following manner:

$$\Sigma(x) \rightarrow U(x)\Sigma(x)V^\dagger(x). \quad (2.32)$$

The chiral Lagrangian can now be written as a sum of Lagrangians of operator dimension 2 to 4 and a self-interaction Lagrangian for the Σ field:

$$\mathcal{L}_{\text{chiral}} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_\Sigma \quad (2.33)$$

and is invariant under $\text{SU}(2) \otimes \text{U}(1)$.

$\mathcal{L}_\Sigma$ can be understood as a generalization of the Higgs potential in Equation 2.17 and is only necessary if fluctuations of the Σ field are allowed¹⁴. In that case it is defined as:

$$\mathcal{L}_\Sigma = -\frac{\mu^2 v^2}{4} \text{Tr} [\Sigma^\dagger \Sigma] + \frac{\lambda v^4}{16} \text{Tr} [\Sigma^\dagger \Sigma]^2. \quad (2.34)$$

The dimension-two Lagrangian is:

$$\mathcal{L}_2 = -\frac{v^2}{4} \text{Tr} [V_\mu V^\mu] - \beta' \frac{v^2}{8} \text{Tr} [TV_\mu] \text{Tr} [TV^\mu]. \quad (2.35)$$

It describes the kinematic of the Σ field and provides the mass terms of the gauge

¹⁴In that case a Higgs boson exists

bosons after electroweak symmetry breaking. V_μ and T are abbreviations for:

$$V_\mu = \Sigma(D_\mu \Sigma)^\dagger \quad (2.36)$$

$$T = \Sigma \sigma_3 \Sigma^\dagger \quad (2.37)$$

which contain the covariant derivative

$$D_\mu \Sigma = \partial_\mu \Sigma + i g \mathbf{W}_\mu \Sigma - i g' \Sigma \mathbf{B}_\mu \quad (2.38)$$

with the fields¹⁵:

$$\mathbf{W}_\mu = W_\mu^a \frac{\sigma_a}{2}, \quad (2.39)$$

$$\mathbf{B}_\mu = B_\mu \frac{\sigma_3}{2}. \quad (2.40)$$

β' is a free parameter, that parametrizes the breaking of the *custodial* symmetry [21].

The dimension-three Lagrangian introduces the fermion mass terms:

$$\begin{aligned} \mathcal{L}_3 = & - (\bar{Q}_L \Sigma M_Q Q_R + \bar{L}_L \Sigma M_L L_R + h.c.) \\ & - \bar{L}_L^c \Sigma^* M_{N_L} \frac{1 + \sigma_3}{2} \Sigma L_L - \bar{L}_R^c M_{N_R} \frac{1 + \sigma_3}{2} L_R. \end{aligned} \quad (2.41)$$

The M_X ($X = Q, L, N_L, N_R$) are mass matrices and $Q_{R/L}, L_{R/L}$ are doublet fields with:

$$Q_{R/L} = \begin{pmatrix} U_{R/L} \\ D_{R/L} \end{pmatrix}, \quad L_{R/L} = \begin{pmatrix} E_{R/L} \\ N_{R/L} \end{pmatrix}. \quad (2.42)$$

The following abbreviations are used for the quark fields: $U \in (u, c, t)$, $D \in (d, s, b)$ and for the lepton fields: $L \in (e, \mu, \tau)$, $N \in (\nu_e, \nu_\mu, \nu_\tau)$. All fermion fields are two-component *Weyl* spinors instead of 4-component Dirac spinors like in the electroweak gauge theory. In the second line of Equation 2.41 also mass terms for neutrino fields are introduced, which are not present in the electroweak theory.

The dimension-four Lagrangian has the following form:

$$\begin{aligned} \mathcal{L}_4 = & -\frac{1}{2} \text{Tr} [\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}] - \frac{1}{2} \text{Tr} [\mathbf{B}_{\mu\nu} \mathbf{B}^{\mu\nu}] + \bar{Q}_L i \gamma_\mu D^\mu Q_L \\ & + \bar{Q}_R i \gamma_\mu D^\mu Q_R + \bar{L}_L i \gamma_\mu D^\mu L_L + \bar{L}_R i \gamma_\mu D^\mu L_R. \end{aligned} \quad (2.43)$$

It describes the kinematic of the gauge boson and fermion fields as well as the interactions between both and do not include Σ fields. The field strength tensors are defined accordingly to Equations 2.6 and 2.7 [22].

¹⁵ σ_a ($a = 1, 2, 3$) are the Pauli matrices

Thus, $\mathcal{L}_{\text{chiral}}$ is the effective Lagrangian at leading order perturbation theory in E/Λ with $\Lambda = 4\pi v \approx 3 \text{ TeV}$ and the typical energy scale E of the subprocess [23].

2.2.3 Anomalous Quartic Gauge Couplings

When calculating next-to-leading order corrections with $\mathcal{L}_{\text{chiral}}$, additional terms are necessary to make the theory finite. This is possible since not all dimension-four operators consistent with electroweak symmetry are included, yet. There are 11 additional dimension-four operators, which conserve CP invariance, but only five of them respect custodial symmetry $\text{SU}(2)_C$ [21]. Two of the five operators are exclusively related to quartic electroweak gauge interactions:

$$\mathcal{O}_4^{(4)} = (\text{Tr} [V_\mu V_\nu])^2 \quad (2.44)$$

$$\mathcal{O}_5^{(4)} = (\text{Tr} [V_\mu V^\mu])^2. \quad (2.45)$$

The chiral Lagrangian is extended by them:

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{chiral}} + \alpha_4 \mathcal{O}_4^{(4)} + \alpha_5 \mathcal{O}_5^{(4)} \quad (2.46)$$

with the two free parameters α_4 and α_5 , referred to as *anomalous quartic gauge couplings* (aQGCs), which are constrained in this work via electroweak gauge boson scattering with the $W^\pm Z jj$ final state.

2.2.4 K-Matrix Unitarization

The two additional operators in Equation 2.46 lead to an unsaturated rise of the cross section with increasing $\sqrt{s}$ and therefore cause a unitarity violation. To prevent this, an unitarization scheme has to be applied. For this work it is the *K-matrix unitarization* [24].

For the analysis of unitarity conditions, the matrix element $\mathcal{M}$ of the elastic scattering process is expanded into its spin I and isospin J eigenamplitudes A_{IJ} . The normalized eigenamplitudes are:

$$a_{IJ} = \frac{1}{32\pi} A_{IJ}. \quad (2.47)$$

For unitarity conversation, the optical theorem of elastic scattering requires the a_{IJ} to respect the so-called *Argant-circle* condition:

$$\left| a_{IJ}(s) - \frac{i}{2} \right| = \frac{1}{2}. \quad (2.48)$$

The Argant-circle is a circle in the complex plane with its center at $i/2$ and a radius

of $1/2$. Normally amplitudes in finite order perturbation theory will not respect this condition. But it is possible to transform an arbitrary amplitude $a(s)$ into an unitary amplitude $a_K(s)$ by the K-matrix unitarization scheme:

$$a_K(s) = \frac{1}{\text{Re}(1/a(s)) - i}. \quad (2.49)$$

Figure 2.2 shows how the K-matrix unitarization method is conducted. The K-matrix method has the advantage, that there are no arbitrary parameters and that the cross section is less suppressed for higher energies than for example with the form factor unitarization scheme.

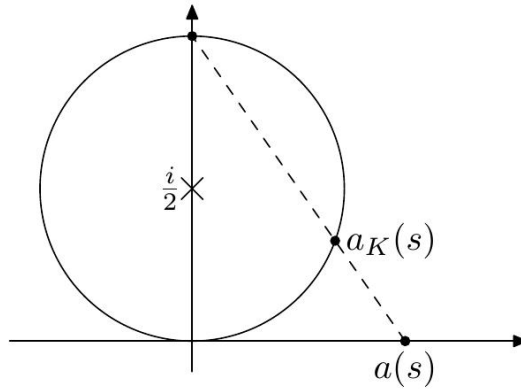


Figure 2.2: K-matrix unitarization scheme [23]. Any real scattering amplitude $a(s)$ is projected on the Argand-circle, resulting in a unitary amplitude $a_K(s)$.

3 Experimental Setup

This chapter introduces the Large Hadron Collider (LHC) and the ATLAS detector, which are the experimental basis for the study of electroweak gauge boson scattering in proton-proton collisions. The LHC accelerates and collides protons, while ATLAS detects final-state particles coming from interactions of these collisions and their decay products and measures their properties.

3.1 Large Hadron Collider

The *Large Hadron Collider* (LHC) [25] is a circular proton-proton accelerator and collider at the *European Organization for Nuclear Research* CERN¹ near Geneva, Switzerland. Currently it is the largest and most powerful particle accelerator world-wide, installed in the tunnel of LHC's predecessor LEP², located around 100 m under the surface with a circumference of 26.7 km.

Since LHC is a particle-particle accelerator, it consists of 2 separate tubes with counter-rotating beams. 1232 superconducting dipole magnets force the beams on their defined trajectories with magnetic fields between 0.45 T and 8.33 T dependent on the beam energy. To keep the magnets superconducting under these extremely high fields, they are cooled down to 1.9 K with superfluid helium. Also, several thousand multipole magnets are used to focus the beams and for other corrections.

Before injecting the protons into LHC, they need to be pre-accelerated with the help of an injector chain [26] (see also Figure 3.1). Starting from a hydrogen source, initially the atoms become ionized and the resulting protons are injected into *Linac2*³ where they are accelerated to an energy of 50 MeV. In the next step, these protons run through the *Proton Synchrotron Booster* (PSB) until they reach an energy of 1.4 GeV and are sent to the *Proton Synchrotron* (PS) where they gain 25 GeV. The last station in the pre-acceleration process is the *Super Proton Synchrotron* (SPS) from where protons with 450 GeV are inserted into LHC. This all does not happen with a continuous proton beam but with separated bunches of $\sim 10^{11}$ protons, due to the fact that the particles are accelerated with radiofrequency cavities at a frequency of 400 MHz by LHC.

¹Acronym for: “Conseil Européen pour la Recherche Nucléaire”, a historical name

²Acronym for: Large Electron Positron Collider, active from 1989 until 2000

³Acronym for: Linear Accelerator 2

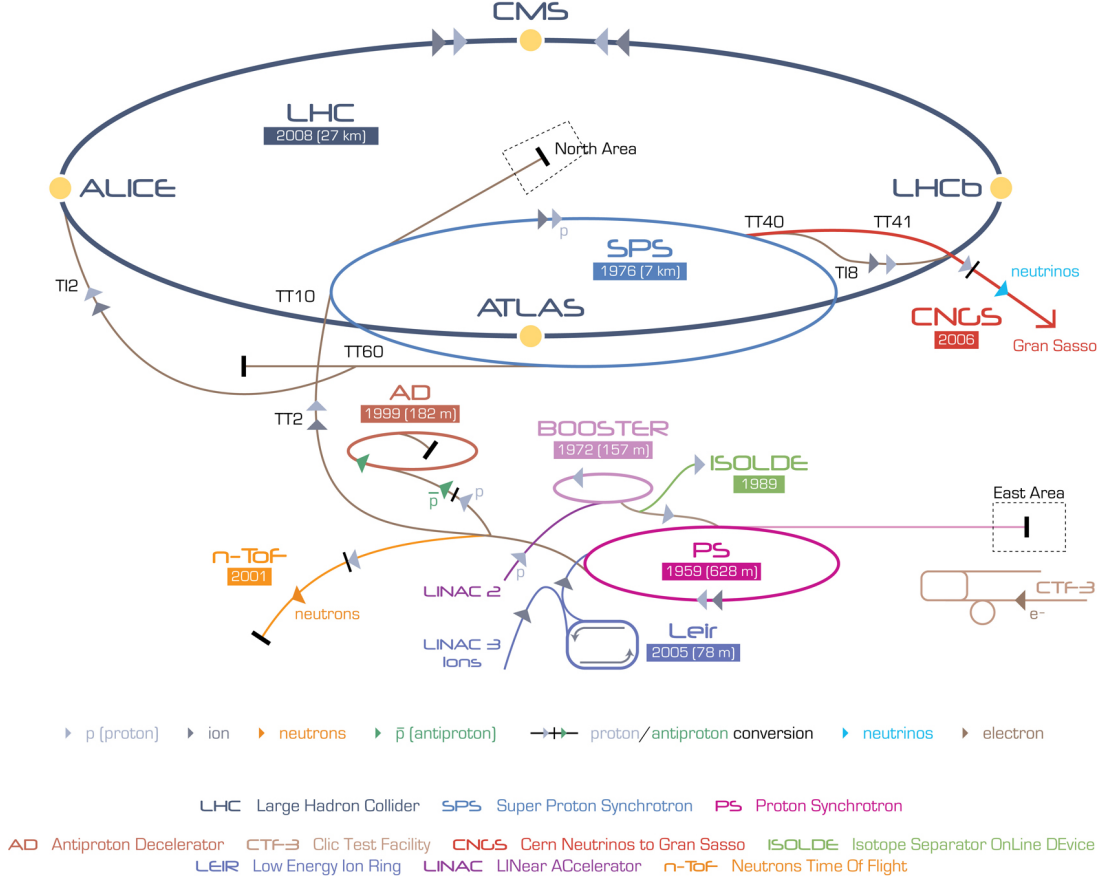


Figure 3.1: Schematic view of the CERN accelerator complex [27].

LHC's design parameters are: proton energies of 7 TeV, resulting in a center-of-mass energy of $\sqrt{s} = 14$ TeV, 2808 bunches per beam with a bunch spacing of 25 ns and a luminosity of $\mathcal{L} \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The luminosity $\mathcal{L}$ is a LHC intrinsic parameter, defined as follows:

$$\mathcal{L} = \frac{N_p^2 n_b f_{\text{rev}} \gamma_r F}{4\pi \varepsilon_n \beta^*}, \quad (3.1)$$

with the number of protons per bunch N_p , the number of bunches per beam n_b , the revolution frequency f_{rev} , the relativistic gamma factor γ_r , the normalized transverse beam emittance ε_n , the beta function at the interaction point β^* , which describes essentially how good the beams are focused and the luminosity reduction F , a geometric factor, required because of the crossing angle between the beams at the collision point. The luminosity links the rate with which events of a special process

p are produced dN_p/dt to the cross section of this process σ_p :

$$\frac{dN_p}{dt} = \mathcal{L} \cdot \sigma_p. \quad (3.2)$$

As the cross sections of the studied processes are often extremely small, a high luminosity is needed to collect useful amounts of data in a finite time. The integral over the time t of $\mathcal{L}$ results in the *integrated* luminosity

$$\mathcal{L}_{\text{int}} = \int \mathcal{L} dt. \quad (3.3)$$

With this the absolute number of expected events of a certain process can be calculated.

This work is based on the run of 2012, where the center-of-mass energy was $\sqrt{s} = 8$ TeV with 1380 bunches per beam and a luminosity of $\mathcal{L} \sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. During the run LHC delivered an integrated luminosity of $\mathcal{L}_{\text{int}} = 23.3 \text{ fb}^{-1}$ (femtobarn: $1 \text{ fb} \equiv 10^{-39} \text{ cm}^2$) [28].

At the interaction points (IP) the beams can be brought to collision. At these points the main experiments are installed: ALICE [29], ATLAS [30], CMS [31] and LHCb [32]. While ATLAS and CMS are multifunctional detectors able to search for new physics of various types, ALICE and LHCb are more specialized. ALICE examines collisions of lead ions⁴ and thereby fundamental QCD topics like the quark-gluon-plasma and confinement. LHCb investigates CP violation through B -meson decays and tries to find reasons for the matter/antimatter asymmetry in our universe.

3.2 The ATLAS Experiment

ATLAS [30] stands for “A Toroidal LHC Apparatus”, it is a general-purpose particle detector, used to search for physical phenomena at previously inaccessible energies. In 2012 a new particle has been discovered, which is believed to be the theoretically predicted and long searched SM Higgs boson. But also phenomena predicted by theories beyond the SM, like *Supersymmetry* or *extra dimensions* are researched with ATLAS.

The detector covers nearly the complete solid angle around the interaction point (IP) and is designed to detect all possible kinds of decay products from particles produced in the proton-proton collisions except for neutrinos. To achieve this, the ATLAS detector encloses the IP with several layers of detector technologies. An overview of the detector is shown in Figure 3.2. The main parts of the detector are the Inner Detector, the electromagnetic and hadronic calorimeters and the Muon

⁴LHC can not only accelerate protons but also lead ions up to a maximal energy is 2.8 TeV per nucleon.

Spectrometer. Particle identification is achieved by evaluating the information delivered by each sub-detector. Also a magnetic system is installed to bend the tracks of charged particles for momentum measurement. The following sections describe these parts as well as the coordinate system used by ATLAS.

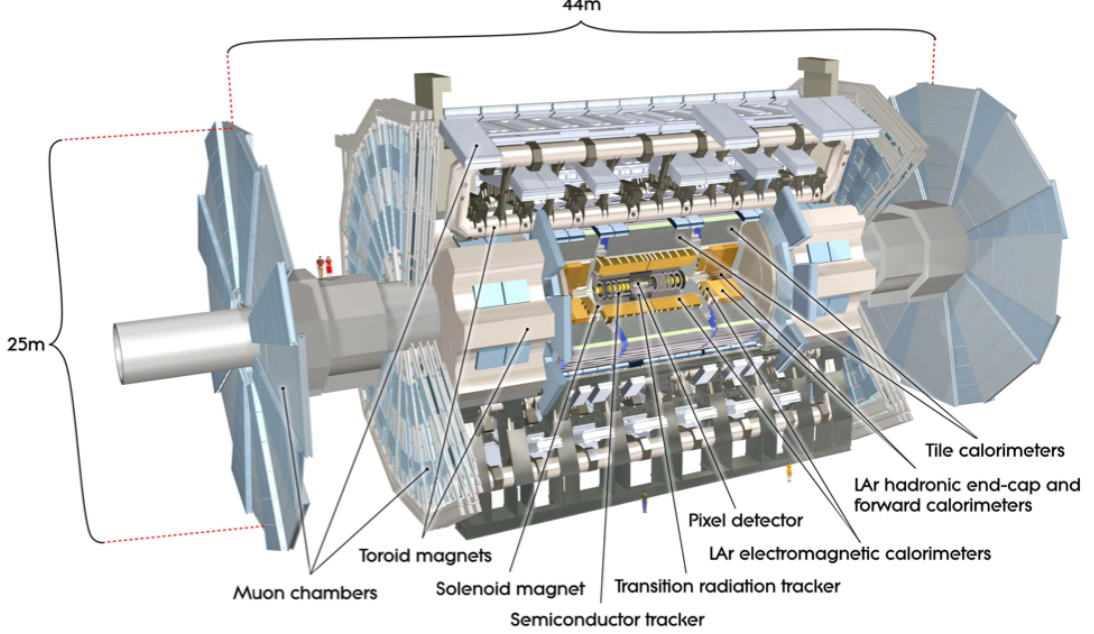


Figure 3.2: Cut-away view of the ATLAS detector [30].

3.2.1 Coordinate System

For the description of the arising particles a right-handed cartesian coordinate system with its origin at the nominal interaction point is used. The x-axis points from the origin to the center of the LHC ring, the y-axis points upwards and the z-axis goes with the beam direction. There are two angles defined: the azimuthal angle ϕ ($-\pi \leq \phi < \pi$) in the x-y plane with $\phi = 0$ for $y = 0$ and the polar angle θ between the particle momentum and the z-axis, starting from the z-axis. In particle physics it is more common to use the pseudorapidity η defined as:

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]. \quad (3.4)$$

With η one can define ΔR :

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}, \quad (3.5)$$

which describes the angular distance between the momentum vectors of two particles or jets in the $\phi - \eta$ space. ΔR is used for isolation criteria in the event and object selection.

The x-y plane is also called *transverse* plane, due to the fact that it is perpendicular to the beam direction. All quantities defined in this plane have an index T , for instance the transverse momentum p_T defined as

$$p_T = \sqrt{p_x^2 + p_y^2}. \quad (3.6)$$

3.2.2 Inner Detector

The Inner Detector (ID) is the component closest to the collision point. It has a cylindrical shape with a length of 7 m and a diameter of 2.3 m and is able to cover a range of $|\eta| < 2.5$. Its main tasks are vertex reconstruction, momentum measurement and charge identification. The ID is surrounded by a superconducting solenoid, which generates a magnetic field of 2 T parallel to the beam direction. This field bends the tracks of the emerging charged particles and through the curvature it is possible to determine the sign of the charge and calculate the momentum. The IP and also secondary vertices can be reconstructed with the help of the tracks. For the reconstruction of secondary vertices coming from intermediate particles the tracks need to be identified with a high spatial resolution. At LHC's design luminosity each collision produces approximately 1000 particles whose tracks and vertices are reconstructed using pattern recognition. The ID is composed of three different, independently and complementary working, subsystems: the *Pixel Detector*, the *Semiconductor Tracker* (SCT) and the *Transition Radiation Tracker* (TRT). A technical overview is given in Figure 3.3. A compromise between precise position measurement and a small energy deposition had to be found to lose as little as possible information before the energy measurement in the calorimeters.

Pixel Detector

The Pixel Detector is the innermost subsystem, it comprises 3 cylindrical layers around the beam pipe and 3 disks at each end-cap with overall 80.4 million silicon pixels covering a range of $|\eta| < 2.5$. The innermost layer has a radial distance of 50.5 mm from the interaction point and all pixels have a spatial resolution of 115 μm in direction of z and 10 μm in the transverse plane. Every charged particle hits at least 3 pixels layers.

Semiconductor Tracker

The Semiconductor Tracker encapsulates the Pixel Detector with its 4 layers in the barrel region and 9 discs at both ends. It is able to cover $|\eta| < 2.5$. Each layer consists

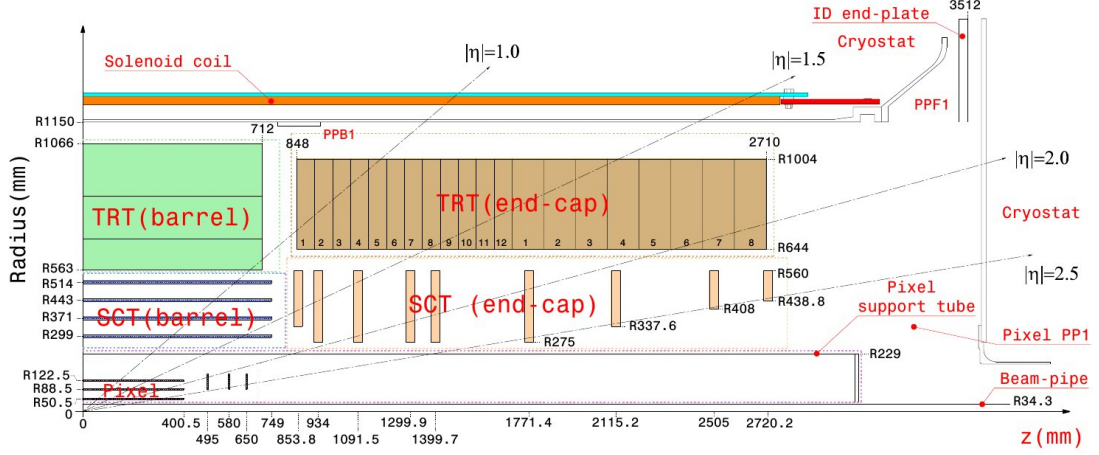


Figure 3.3: Profile of the Inner Detector [30]. Shown is a quarter-section with the Pixel Detector (Pixel), the Semiconductor Tracker (SCT), the Transition Radiation Tracker (TRT) and the solenoid system.

of a set of 2 silicon microstrip layers with a stereo angle of 40 mrad between them, to allow the measurement of both coordinates. Every track hits 8 microstrip layers resulting in 4 points for track reconstruction. With its 6.3 million readout channels a resolution of 17 μm in the transverse plane and 580 μm in z can be achieved. The reason for the relatively low resolution in z is the small stereo angle, which can not be larger due to technical limitations.

Transition Radiation Tracker

The outermost part of the ID is the Transition Radiation Tracker. It can identify electrons as well as providing track information. Therefore straw detectors are used, every staw has a diameter of 4 mm, filled with a gas mixture of 70% Xe, 27% CO₂ and 3% O₂ and a 30 μm thick anode wire going through its center. Every charged particle with $p_T > 500 \text{ MeV}$ and $|\eta| < 2.0$ hits as many as 36 straws, except for the transition region between barrel and end-cap ($0.8 < |\eta| < 1.0$) where at least 22 straws are crossed. The barrel region has 73 straw layers, with straws parallel to the beam axis at a length of 144 cm. The straws are separated in the middle and every half is read out individually. Each end-cap consists of 160 straw planes with 37 cm long straws running radially from the beam pipe. Incoming charged particles ionize gas atoms along their tracks and an electric field accelerates the arising ions to an electrode, where they are collected, producing a measureable signal.

For electron identification, transition radiation material is located between the straws, wherein electrons produce photons, which are detected with the help of the Xenon in the gas mixture. The signal amplitude of the transition radiation is much larger than the amplitude caused by ionisation, so two thresholds are used to distin-

guish both.

The Transition Radiation Tracker reaches a spatial resolution of $130\text{ }\mu\text{m}$ per straw in the transverse plane through drift time measurements. The z coordinate can not be measured.

3.2.3 Calorimeter System

The calorimeter system surrounds the Inner Detector and the solenoid. Its purpose is the energy measurement of charged and neutral particles by absorbing them. Especially for the missing transverse energy $E_{\text{T}}^{\text{miss}}$ measurement a coverage of the complete solid angle would be desirable. This is not feasible, but the calorimeter covers the complete azimuthal angle and a range of $|\eta| < 4.9$, ensuring a good $E_{\text{T}}^{\text{miss}}$ resolution.

The calorimeter system is composed of two separate calorimeters, an electromagnetic and a Hadronic Calorimeter. Both sub-systems are sampling calorimeters. These calorimeters consist of layers of two materials, an absorber and an active layer, continuously stacked on each other. Incoming particles traversing the absorbers producing secondary particles whose energy is then measured in the active layers. This process is repeated several times until the complete energy of the initial particle is deposited in the calorimeter. In Figure 3.4 an overview of the calorimeter system is shown and in the following paragraphs the sub-detectors are described in more detail.

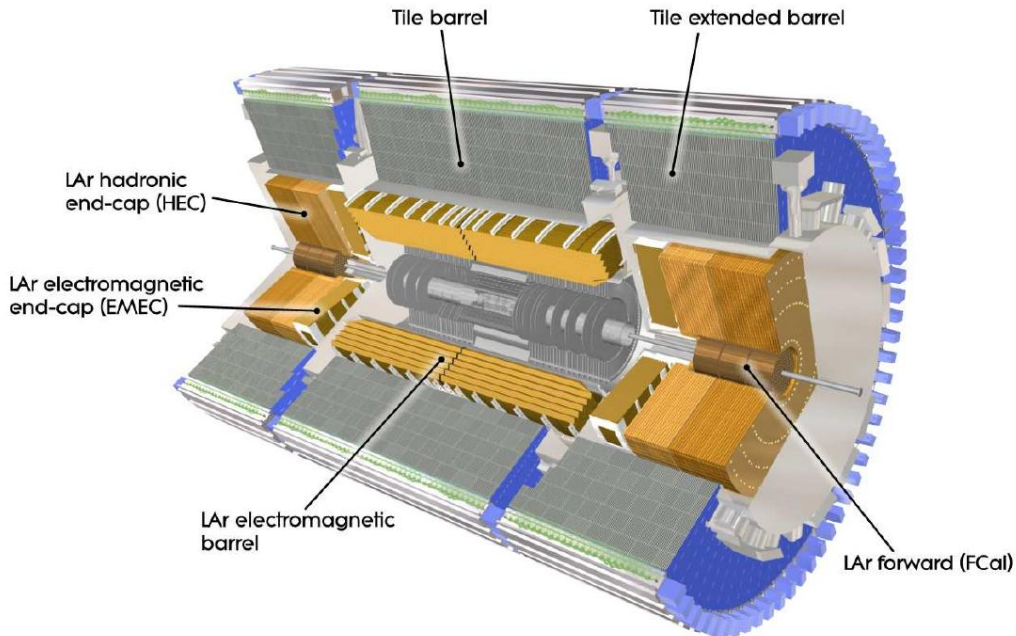


Figure 3.4: Cut-away view of the ATLAS calorimeter system [30]. In the center, the Inner Detector is shown in light grey.

$|\eta| < 1.7$ a tile sampling calorimeter is used with steel as absorber and plastic scintillator tiles as active material. It is complemented by two LAr Hadronic End-cap Calorimeter, covering $1.5 < |\eta| < 3.2$, using copper as the absorber material and LAr as active material. For the high pseudorapidity region ($3.1 < |\eta| < 4.9$) Forward Calorimeters on both sides, installed 4.7 m from the IP, perform hadronic and electromagnetic measurements. Each Forward Calorimeter is divided into 3 successively arranged segments, the one closest to the IP performs electromagnetic calorimetry with a copper absorber, while the other two measure the energies of hadrons, with tungsten being used for absorption. The active material for the complete Forward Calorimeter is again LAr.

3.2.4 Muon Spectrometer

The outermost part of the ATLAS detector is the Muon Spectrometer. Apart from muons, only a very small number of particles is expected to traverse the calorimeter, thus the Muon Spectrometer is used to identify muons and measure their momenta. The momentum is measured over the bending of the muon tracks in a magnetic field of 0.5 T in the barrel and 1 T in the end-cap region, which is provided by superconducting toroidal magnets. In a region up to $|\eta| < 2.7$ the track measurement is performed with *Monitored Drift Tube* (MDT) chambers, while for the high rapidity region ($2.0 < |\eta| < 2.7$) additionally *Cathode-Strip Chambers* (CSC) are used. *Resistive Plate Chambers* (RPC) and *Thin Gap Chambers* (TGC) are used to provide information for the trigger system and measure the track coordinate orthogonal to one measured by the MDTs and CSCs in a region up to $|\eta| < 2.4$. In Figure 3.6 the profile of the Muon Spectrometer is shown.

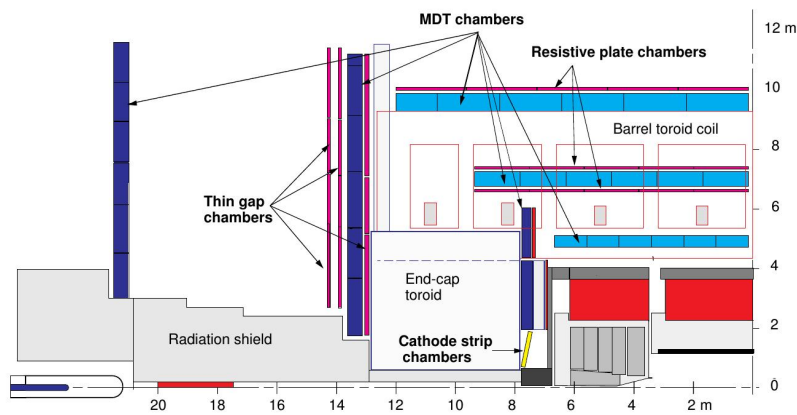


Figure 3.6: Profile of the Muon Spectrometer in the y-z plane [30].

3.2.5 Trigger System

One LHC design parameter is a bunch spacing of 25 ns, which corresponds to a collision rate of 40 MHz. Due to technical and storage limitations only a rate of 200 Hz can be recorded. Since the cross section of the physically interesting processes is many orders of magnitude smaller than cross sections of QCD processes, it suffices to record only a small subset of all events, which have to be selected. This task is performed by the trigger system. It comprises 3 levels, namely *Level-1* (L1), *Level-2* (L2) and the *Event Filter*.

The L1 trigger is completely hardware-based, it decides in 2.5 μ s whether to keep or reject an event based on a subset of the complete detector information and reduces the rate to 75 kHz. It utilizes the muon trigger system to find high p_T muons and the Inner Detector as well as the calorimeter system with a reduced granularity to search for electrons, photons, hadrons from tau decays, jets and large missing transverse energy as well as high overall transverse energy. It also defines so called *regions of interest* (RoI), containing the detector areas and the passed criteria of the objects, which made the trigger to accept the event. During the time it takes the L1 to decide, the event information are written to a buffer.

The L2 trigger uses the data of these RoIs with full granularity and precision to decide via additional selection criteria whether to accept the event. This decision takes about 40 ms and is based on software algorithms performed by a computing cluster. The rate is reduced to about 3.5 kHz.

Finally, the Event Filter decides whether the event is stored permanently by involving offline analysis procedures. This happens also software-based and takes approximately 4 s. It reduces the rate to 200 Hz.

3.2.6 Luminosity Measurement

For the search of new phenomena predicted by some theory, a crucial point is a precisely measured luminosity, as it relates the theoretical cross section directly to the expected event rate as shown in Equation (3.2). The luminosity calculation on the basis of the LHC beam parameters (see Equation (3.1)) has a rather large uncertainty of about 20%, on this account two additional detectors are used to measure the luminosity: ALFA⁵ and LUCID⁶.

The two LUCID detectors are located at both ends of ATLAS in a distance of 17 m from the IP directly around the beam pipe. They detect inelastic proton-proton scattering in a pseudorapidity region $|\eta| \approx 5.8$ using the measurement of Cherenkov light. The luminosity is then determined under the assumption that the number of detected particles is proportional to the number of interactions per bunch crossing. LUCID also provides an online luminosity monitoring.

⁵acronym for: Absolute Luminosity For ATLAS

⁶acronym for: LUMinosity measurement using a Cherenkov Integrating Detector

ALFA consists of two detectors as well, which are installed in a distance of 240 m from the IP. Here detectors (called *Roman pots*) are mounted directly to the beam pipe with only a thin window separating them from the pipe's vacuum. This way the detectors are only 1 mm away from the beam. ALFA measures elastic proton-proton scattering, because the elastic scattering amplitude in the forward region is related to the total cross section via the *optical theorem*.

With these detectors the luminosity can be measured with high precision. For the 2012 data the luminosity uncertainty is $\Delta\mathcal{L}/\mathcal{L} = 2.8\%$.

3.2.7 Data Quality

The ATLAS detector is an extremely sophisticated apparatus. Technical problems arise from time to time and temporarily parts of the detector do not work properly. All the subsystems are monitored continuously to identify and fix emerging issues quickly and to decide whether events taken in this time were measured reliably or if a subsystem returned corrupt data.

The data-taking time is divided into so called *luminosity blocks* (LB) of a length of about 2 min. A flag is assigned to each LB reflecting the detector's status. All the flags are collected in so-called *Good Run Lists* (GRL). With the appropriate GRL for the data used in this work⁷, the integrated luminosity used by ATLAS can be calculated on the website: <https://atlas-lumicalc.cern.ch/>. It amounts to $\mathcal{L}_{\text{int}} = 20.281 \text{ fb}^{-1}$.

⁷data12_8TeV.periodAllYear_DetStatus-v61-pro14-02_DQDefects-00-01-00_PHYS_StandardGRL_All_Good.xml

4 Electroweak Gauge Boson Scattering

This chapter introduces electroweak gauge boson scattering, which is also referred to as *vector boson scattering* (VBS) for historical reasons¹. It is part of the SM and contains quartic electroweak gauge boson vertices, which are modified by anomalous quartic gauge couplings (aQGCs). For that reason, α_4 and α_5 introduced in Chapter 2.2 can be constrained by studying such VBS processes. For this work, the main focus will be on the VBS process with the $W^\pm Z jj$ final state. Its backgrounds are explained at the end of this chapter.

4.1 Definition

In a first approach one would classify all $VV \rightarrow VV$ processes as electroweak gauge boson scattering. And since gauge bosons can not be accelerated separately, they are radiated by quarks in proton-proton interactions at the LHC, resulting in $VVjj$ final states, because these quarks are detected as two high energetic, so-called *tagging jets* j . The electroweak gauge bosons V can decay either leptonically or hadronically and are detected by their decay products. Only the leptonic decays are considered here, because of the clean lepton signatures in the detector, which allow a precise object reconstructions. Figure 4.1 shows a Feynman diagram representing VBS processes, the grey dot is a wildcard for the possible gauge boson interactions, which are shown in Figure 4.2. These processes are not gauge invariant on their own and additional Feynman diagrams are necessary. Examples are shown in Figure 4.3a and 4.3b, by shifting the vertices to other propagators one obtains all possibilities.

One can classify $VVjj$ processes into two subsets: $VVjj$ -EW and $VVjj$ -QCD processes:

- $VVjj$ -EW includes all tree-level Feynman diagrams, which have the same final states and whose square of the absolute value of the matrix element $|\mathcal{M}|^2$ is at order 6 in the electroweak coupling α_{ew} and at order 0 in the strong coupling α_s in leading order perturbation theory in EW and QCD. That means, Feynman

¹The term *vector boson scattering* is rather imprecise, because in the SM all particles with spin 1 are vector bosons, that includes gluons as well as composite particles like mesons, but intended are the electroweak gauge bosons $W^\pm$, Z , and γ summarized as V .

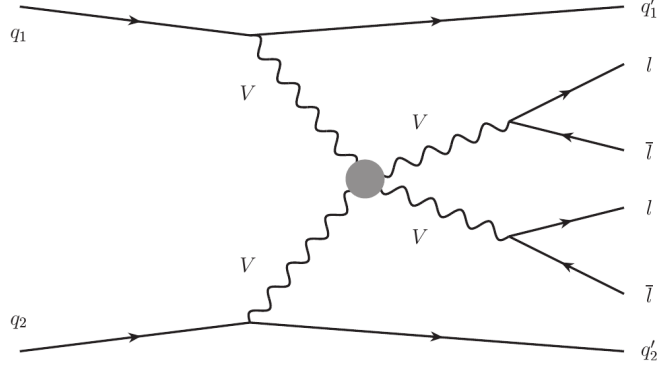


Figure 4.1: Feynman graph representing electroweak gauge boson scattering with quarks q_i/q'_i , gauge bosons V and leptons $l/\bar{l}$. Only the fully leptonic final state for W and Z is considered here. The grey dot in the center is a wildcard for the possible gauge boson interactions, which are shown in Figure 4.2.

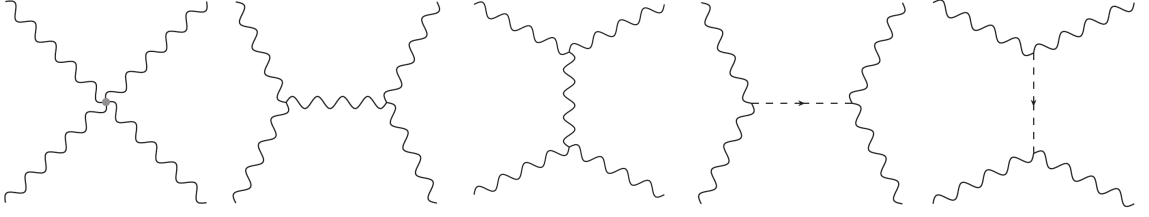


Figure 4.2: Feynman diagrams of the possible electroweak gauge boson interactions. The wiggly lines represent gauge bosons V and the dashed lines the SM Higgs boson H . Not all diagrams are allowed for all processes.

diagrams, which are not necessary for conserving gauge invariance, are included. Examples are plotted in Figure 4.3c and 4.3d.

- $VVjj$ -QCD includes all tree-level Feynman diagrams with $|\mathcal{M}|^2 \propto \mathcal{O}(\alpha_{\text{ew}}^4 \alpha_s^2)$. Examples are given in Figure 4.4. These processes have the same final state as $VVjj$ -EW but a different coupling structure.

4.2 $W^\pm Zjj$ Gauge Boson Scattering

Electroweak gauge boson scattering with the $W^\pm Zjj$ final state is analysed in this work to constrain the aQGCs α_4 and α_5 . It also includes $W^\pm \gamma^* jj$ with a virtual photon γ^* , because it is indistinguishable from $W^\pm Zjj$. The electroweak $W^\pm Zjj$ -EW as well as the strong $W^\pm Zjj$ -QCD production are predicted by the SM but not yet observed. The $W^\pm Zjj$ -EW processes are defined as signal in further considerations. As already mentioned only fully leptonic final states of the gauge boson decays are

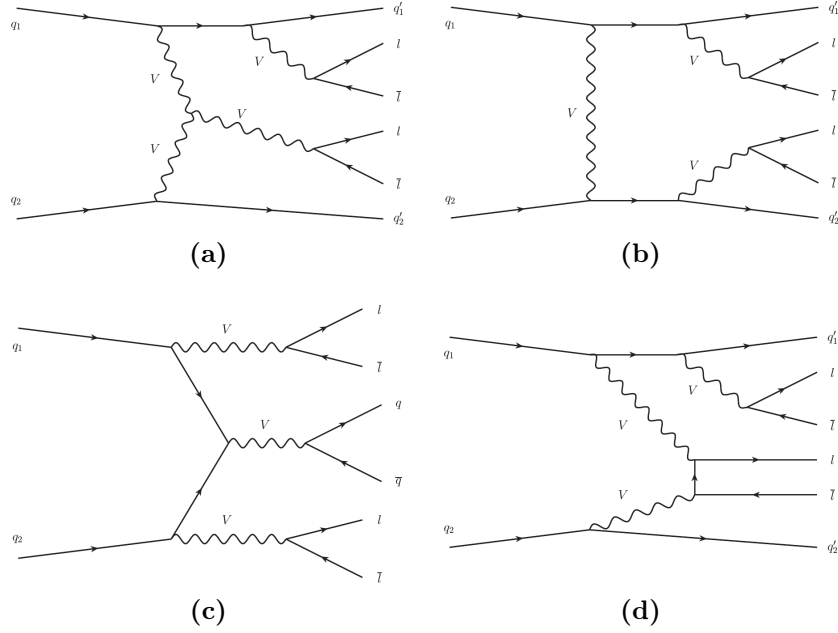


Figure 4.3: Additional Feynman diagrams, which are added to VBS for the definition of $VVjj$ -EW. (a) and (b) are examples of Feynman diagrams, which are necessary to ensure gauge invariance. (c) and (d) are gauge invariant separabel, but are included in to the signal. These are not all possible diagrams, but by shifting the vertices to other propagators one obtains the remaining possibilities.

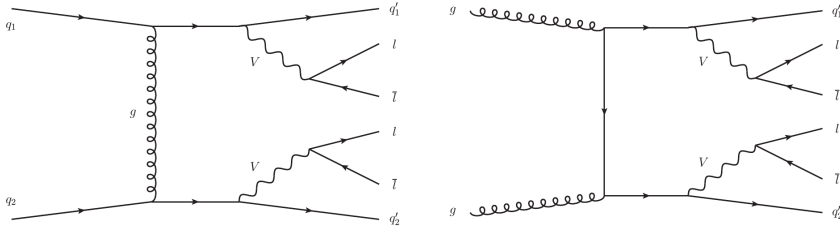


Figure 4.4: Feynman diagrams of $VVjj$ -QCD. These diagrams are at order $\mathcal{O}(\alpha_{\text{ew}}^4 \alpha_s^2)$. The curly lines are gluon propagators.

studied² and of them only final states consisting of electrons, positrons and (anti-)muons, that means there are four different decay channels, when neglecting the electromagnetic charge of the charged lepton from the W decay:

1. The **eee-channel** consists of final states with two electrons (positrons) and one positron (electron).

²Except for the gauge invariant separabel processes with 3 gauge bosons, where one must decay hadronically, to have an appropriate final state.

2. The **eem-channel** comprises all final states with one electron, one positron and one muon/antimuon.
3. The **mme-channel** consists of final states with one muon, one antimuon and one electron/positron.
4. The **mmm-channel** consists of final states with a muon-antimuon pair coming from the Z boson and a muon/antimuon from the W boson.

All channels come with an additional neutrino compatible with the lepton from the W decay. This is only noticeable through large missing momentum in the detector (cf. Chapter 5.1.6).

4.3 Background Processes for $W^\pm Z jj$ -EW

Several SM processes have the same final state as $W^\pm Z jj$ -EW or mimic it, due to mis-identification of jets as leptons or conversion of photons. The fiducial phase space (see Chapter 5.2) is defined to suppress all possible backgrounds as good as possible on the basis of differences of kinematic distributions to the signal, while losing as little signal as possible. The contributing backgrounds are:

- **$W^\pm Z jj$ -QCD**: This background contributes most, because it has the same final state as the signal and an approximately 20 times larger cross section³. But it can be well suppressed by requiring events with an invariant mass of the tagging jets $M(j_1, j_2) > 500 \text{ GeV}$., which is done in the definition of the fiducial phase space in Chapter 5.2.
- **ZZ** : This underground only contributes, if one lepton is not properly reconstructed in the dileptonic decay $Z \rightarrow l^+ l^- l^+ l^-$ because the fiducial phase space definition uses a ZZ veto by requiring exactly 3 leptons with $p_T > 7 \text{ GeV}$. Furthermore, the Z mass requirement for same flavour, opposite charge leptons $|M(l_i, l_j) - M_Z| < 10 \text{ GeV}$ reduces contributions from virtual photons γ^* .
- **$t\bar{t}V$** : For this background the V represents W and Z . The larger contribution comes from $t\bar{t}Z$ because such events are more likely to pass the Z mass requirement. The tops decay with the highest probability into $b l \nu$.
- **$t\bar{t}$** : For this background an additional lepton is needed to pass the event selection, this can come from a jet, which is misidentified as a lepton, from photon

³This ratio is calculated in leading order QCD and EW with SHERPA for an extended phase space, which is defined by requiring invariant masses between all pairs of leptons in an event $M(l_i, l_j) > 4 \text{ GeV}$, transverse momenta of all leptons $p_T^l > 5 \text{ GeV}$ and transverse momenta of all jets $p_T^j > 15 \text{ GeV}$.

conversion or heavy quark decays. Since the lepton does not emerge from the actual decay, this background is referred to as *fake background*.

- **$Z\gamma$** : The Z decays leptonically and the photon needs to be converted into an electron, this is a fake background as well.
- **$Z + \text{jets}$** : For this background the jet needs to be misidentified as an electron, while the Z must decay leptonically. Therefore, this is also a fake background.

For each of these backgrounds separate Monte Carlo sample are generated (for event simulation see Chapter 6). They can be found in Appendix B. The fake backgrounds are not well modeled by Monte Carlo samples and discrepancies between data and simulation are observed, therefore these backgrounds have to be estimated from data. This was not feasible on the timescale of this work.

5 Object Reconstruction and Signal Event Selection

5.1 Object Reconstruction and Selection

The required physical objects for the study of the $W^\pm Zjj$ electroweak gauge boson scattering are electrons, muons, neutrinos and quarks/gluons. Neutrinos does not interact with the detector materials and are therefore only observable through large missing transverse momentum E_T^{miss} . Quarks/gluons are not directly observable, since they carry the strong charge and confinement prohibits free strong charged particles. They are represented by jets.

This section introduces the reconstruction of the relevant objects from the signatures in the ATLAS detector induced by proton-proton collisions as well as the signatures from simulated events introduced in Chapter 6. Furthermore, the selection criteria for accepting reconstructed objects are specified.

5.1.1 Trigger

The ATLAS trigger system is introduced in Section 3.2.5. For the selection of interesting events electron and muon triggers are utilized. The Level-1 (L1) electron trigger measures the energy deposition of electromagnetic clusters, while the L1 muon trigger performs a p_T measurement with the track information in the Muon Spectrometer (MS). For passing the trigger selection a $p_T > 25 \text{ GeV}$ is required for at least one electron or muon. Additional requirements have to be fulfilled to pass the Level-2 trigger and the Event Filter.

5.1.2 Primary Vertex

At high luminosity multiple interactions occur per bunch crossing. Vertices are reconstructed with the *iterative vertex finding algorithm* [33] by clustering tracks with a compatible z-position along the beamline and make a fit. Now, one has to select one distinguished vertex. This one is called *primary vertex* and is defined as the vertex with the highest value for $\sqrt{\sum p_T^2}$, where the sum is taken over all reconstructed tracks associated with the vertex [34]. Objects assigned to this vertex are of interest and will be reconstructed.

5.1.3 Electrons

Electrons are reconstructed by clustering the energy depositions in the electromagnetic (EM) calorimeter and associating the cluster to a track in the Inner Detector (ID) coming from the primary vertex. Electron candidates have to pass the 2012 “loose++” requirements recommended by the ATLAS Egamma working group [35]. They need $p_T > 15 \text{ GeV}$ and must be in a pseudorapidity region of $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ to ensure complete tracking information in the ID and avoid inaccurate energy measurement in the transition region of the EM calorimeter. They also have to pass additional track and calorimeter isolation requirements. If an electron is inside the cone around a muon with $\Delta R < 0.1$ (defined in Equation 3.5), it will be rejected. If the event was triggered by an electron, it is necessary for at least one electron candidate to have a $p_T > 25 \text{ GeV}$ and its track has to match within a cone of $\Delta R < 0.1$ with the trigger object.

5.1.4 Muons

Muons are reconstructed with the so-called STACO algorithm and have to pass the requirements recommended by the Muon Combined Performance Group [35]. There are two types of reconstructed muons: combined (CB) and segment tagged (ST) muons. CB muon reconstruction uses a combination of track information from the ID and the MS, while ST muons are reconstructed from track information of the ID harmonized to at least one segment of the MS. The ST reconstruction is only utilized for tracks and segments not already used by the CB reconstruction. Muon candidates need to fulfill $p_T > 15 \text{ GeV}$ and $|\eta| < 2.5$ as well as additional track isolation requirements. Their energy is corrected for losses by traversing the calorimeter system. When a muon was triggered the p_T of at least one muon candidate must be above 25 GeV and its track must be located inside a cone of $\Delta R < 0.15$ around the trigger object to accept the event.

5.1.5 Jets

Jets are cascades of hadrons and electromagnetic particles originating from quarks and gluons. They are reconstructed using the anti- k_T clustering algorithm [36] with the radius parameter $R = 0.4$ for the clustering of the energy depositions in the hadronic and EM calorimeter and the formation of jets. Jets have to have $p_T > 30 \text{ GeV}$ and $|\eta| < 4.5$. The *jet vertex fraction* (JVF) is defined as the probability that a jet originates from the primary vertex and it is required to be $\text{JVF} > 0.5$ for jets in the region $|\eta| < 2.4$. This requirement is applied to eliminate jets from pile-up. Figure 5.1 illustrates the definition of the JFV. If a jet overlaps with the cone of any selected lepton within $\Delta R < 0.3$, the jet will be removed.

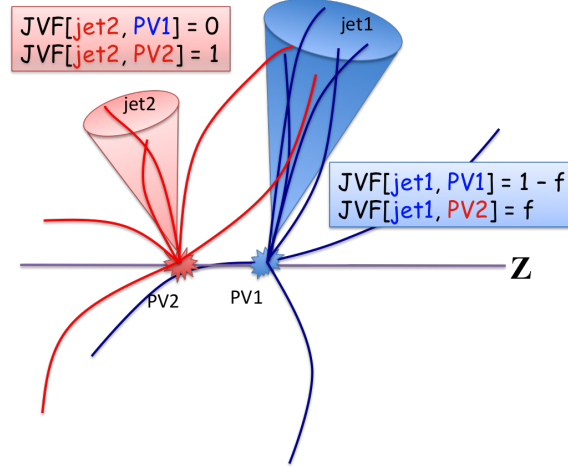


Figure 5.1: Schematic Description of the jet vertex fraction (JVF) [37]. It is defined as the probability that a jet originates from the primary vertex (PV).

5.1.6 Missing Momentum

The missing momentum E_T^{miss} is defined as the transverse momentum imbalance in the detector. Since the momentum of the interacting partons from the accelerated protons is unknown, but they have virtually no transverse momentum, the reason for the imbalance can only be neutrinos, assuming all other particles have been detected. E_T^{miss} is calculated by summing up the transverse momenta of all reconstructed objects as well as clustered energy depositions in the detector which are not associated with any particles referred to as *soft term* transverse energy. Only clustered depositions are considered to avoid the inclusion of detector noise. Jets within $|\eta| < 2.4$ with $p_T < 50 \text{ GeV}$ and a $\text{JFV} \leq 0.5$ are excluded from the calculation, because it is highly probable they originate from pile-up.

5.2 Signal Event Selection

This section introduces the selection criteria for signal events. The objective of the selection is a as good as possible suppression of inevitable background events, while being still sensitive to the signal process. Only events with fully leptonic final states from $W^\pm$ and Z decays are considered due to their distinctive signatures in the detector. For the signal event selection a so-called *fiducial phase space* region is defined with selection criteria close to the object selection. The event selection criteria are:

- The 3 reconstructed leptons with highest p_T are selected as candidates from the $W^\pm$ and Z decays to suppress the contribution of leptons arising from jets.. They are “dressed”, that means the sum of the four-momenta of photons

from QED radiation within a cone of $\Delta R < 0.1$ is added to the lepton's four-momentum. The dressed leptons are then required to have a $p_T(l) > 15 \text{ GeV}$ and $|\eta| < 2.5$.

- Each event is required to have exactly 3 leptons with $p_T > 7 \text{ GeV}$ to suppress contributions from $ZZ \rightarrow lll$
- For a Z candidate an event with 2 leptons with the same flavour and opposite charge are necessary. Their invariant mass $M(l_1, l_2)$ is required to be inside a Z mass window of $|M(l_1, l_2) - 91.1876| < 10 \text{ GeV}$.
- For a $W^\pm$ candidate a third lepton with $p_T(l_3) > 20 \text{ GeV}$ is required and the transverse W mass

$$M_T(W) \equiv \sqrt{2p_T(l_3)E_T^{\text{miss}}(1 - \cos[\Delta\phi(l_3, E_T^{\text{miss}})])} \quad (5.1)$$

must be larger than the 30 GeV .

- An event must have at least two jets, since the final state of the $W^\pm Zjj$ scattering has 2 quarks in the final state.
- All jets in the event are required to have a $p_T > 30 \text{ GeV}$ and $|\eta| < 4.5$. The two jets with the highest p_T are referred to as *tagging jets* and are utilized for the suppression of pile-up.
- The invariant mass of the tagging jets $M(j_1, j_2)$ must be $M(j_1, j_2) > 500 \text{ GeV}$. This criteria suppresses greatly the $W^\pm Zjj$ QCD background.
- The isolation criteria are:
 - $\Delta R(l_1, l_2) > 0.2$ between the Z leptons¹,
 - $\Delta R(l_i, l_3) > 0.3$ ($i = 1, 2$) between the Z leptons and the W lepton,
 - $\Delta R(l, j) > 0.1$ between all selected leptons and jets and
 - $\Delta R(j, j) > 0.4$ for all selected jets.

Only events that pass all this criteria are used for the $W^\pm Zjj$ EW analysis.

¹The expression Z lepton as well as W lepton are used for leptons emerging from a Z or $W^\pm$ decay, respectively.

6 Event Simulation

Theory predictions of a physical model need to be compared to the data of high energy experiments to test the compatibility of the theory with the experimental outcome. Furthermore, backgrounds for a certain process have to be estimated as well as detector efficiencies. This can be achieved by event simulation¹. In the next section the steps are described, which are necessary to produce such events — starting from the theory — in a manner that they can be compared to data achieved by a detector and used for estimations.

6.1 Event Simulation Chain

The event simulation is processed event by event, since there are no correlations between 2 events. The complete simulation can be divided into two main parts: the *event generation* and the *detector simulation*.

In the event generation the following steps are processed successively by Monte Carlo event generators:

1. The matrix element of the relevant scattering process is integrated over the available phase space. The integration is performed numerically involving the Monte Carlo method [38], because usually those integrals are not analytically solvable. The usage of this method in several steps of the generation is the reason that the generators are referred to as Monte Carlo generators.
2. Events are generated in accordance with the phase space boundaries by involving again the Monte Carlo method. Since ATLAS investigates the collision of protons and therefore the interaction of partons² forming the proton, Monte Carlo generators need *parton distribution functions* (PDFs) as input, which describe the frequency of the different partons in a proton as a function of the momentum fraction x of the proton's momentum. The output of the event generation are particles described by their particle IDs, positions, four-momenta and so on. This stage of the simulation is referred to as *parton level*.
3. The next step is the *parton shower*. This name originates from the fact, that the partons produce a cascade of other partons, called shower. The reason is

¹The outcome of a collision of two particles with all its decay products is referred to as an *event*

²Partons are the generic term for quarks and gluons.

that they carry the charge of the strong interaction also known as color and in analogy to QED the partons undergo QCD-bremsstrahlung by for example radiating gluons, which are charged themselves and do likewise bremsstrahlung. In this step also the decay of tau leptons is simulated as well as QED radiation.

4. After the shower the energy of the partons is low enough to form colorless hadrons. This step is referred to as *hadronization* and it is non-perturbative, due to the low energy of the partons, which are no longer asymptotically free. Hence, phenomenological models have to be used for description. This stage is referred to as either *particle level* or *truth level*, since there are no detector effects included.

The particle records coming from the event generation are the input for the detector simulation, where the response of the detector to the incoming particles is simulated. Mainly two possibilities for detector simulation exist:

1. The *full simulation* uses the program GEANT4 [39], which has a mapping of the entire ATLAS detector. The interactions of every particle and emerging secondary particles with the detectors are simulated in full granularity for a precise simulation of the detector response. This simulation is extremely CPU-intensive.
2. The *fast simulation* is performed with ATLFast-II [40], which consists of two components: the Fast ATLAS Tracking Simulation (FATRAS), for the Inner Detector and the Muon Spectrometer and the Fast Calorimeter Simulation (FastCaloSim), which simulates the calorimeters. The fast simulation is by a factor of 100 faster than the full simulation through simplified descriptions of the detectors. The default for ATLFast-II is to use FastCaloSim in combination with GEANT4 for the simulation of Inner Detector and Muon Spectrometer.

The detector simulation produces hits in the cells of the detector.

The subsequent step is the *digitization* where the hits are converted into so-called “digits”. A digit is created when the energy deposition of a hit causes a voltage or current above a predefined threshold. Before the digitization is executed, the hits of the detector simulation are superimposed with hits coming from numerous other interactions to simulate *pile-up*, which is a collective term for all processes that overlay the actual event, these are for example multiple interactions in one bunch crossing, interactions with the beam gas, the cavern background and the detectors are also sensitive to parton interactions of several different bunch crossings. After this step, the simulated events and the actual data have the same data format.

The last step is the *object reconstruction*, which is the same for the experimental data and the simulated events. Here the track and energy information are used to reconstruct particles and jets with their momenta and energies and the missing momentum E_T^{miss} is calculated [41]. This stage is referred to as *reconstruction level*.

6.2 Simulation Corrections

The detector simulation is not able to perfectly describe the real ATLAS detector. On the one hand the used physical models are approximations of the reality and are limited in detail due to computing resource limitations and on the other hand the detector conditions change during the data-taking period such as the beam conditions change and by association the pile-up, also defects emerge during the run and need to be considered. The simulated events need to be corrected for those effects.

Lepton Energy and Momentum Corrections

Muon momentum resolution and scale correction factors as a function of the pseudorapidity η are derived with the help of dedicated measurements of clean $Z \rightarrow \mu^+\mu^-$, $J/\psi \rightarrow \mu^+\mu^-$ and $\Upsilon \rightarrow \mu^+\mu^-$ decays by comparing the shape of the di-muon invariant mass distributions to simulated data of the same processes [42]. This is accordingly done for electron resolution corrections with measurements of $Z \rightarrow e^+e^-$ decays [43]. These corrections are applied to all reconstructed muons respectively electrons of the simulated events before object selection.

Lepton Efficiency Corrections

To account for mismodeling in the reconstruction of simulated events, the reconstruction, identification and isolation efficiencies of electrons and muons are determined utilizing a *tag-and-probe method*. This method is used with simulated and measured $Z \rightarrow e^+e^-$ and $J/\psi \rightarrow e^+e^-$ decays for electrons [44] and $Z \rightarrow \mu^+\mu^-$ decays for muons [42, 45]. The determined electron efficiencies are functions of η and E_T , while the muon efficiencies are functions of η , p_T and ϕ . Scale factors are derived from the differences between simulated and measured efficiencies and are applied to all simulated electrons and muons, respectively.

Since electron and muon triggers are used to trigger on potential events of interest, the same thing is done for the trigger efficiencies to determine the trigger scale factors.

Jet Energy Corrections

Jets are corrected for energy contributions from pile-up, the jet direction is corrected in a manner, that a jet originates from the primary vertex instead the geometrical center of the detector and the jet energy is corrected by constant factors accounting for differences between kinematic distributions of reconstructed and Monte Carlo truth jets [46].

Missing Momentum Corrections

The missing momentum E_T^{miss} is the transverse momentum imbalance in the detector and is derived by summing up the transverse momenta of all reconstructed particles (and additional calorimeter clusters without a reconstructed particle, as described in Section 5.1.6) as a consequence the corrections to the energies and momenta of these particles have to be propagated to E_T^{miss} .

Pile-up Corrections

Often simulations are processed before the actual measurement, in this case the pile-up can only be estimated as a constant, which is in bad agreement with the reality, because it changes with changing beam conditions, e.g. different instantaneous luminosities to different times or changes in bunch spacing. Therefore, the simulated events need to be reweighted to fit to the actual conditions.

6.3 The Event Generator WHIZARD

WHIZARD [47] is an universal Monte Carlo event generator for the integration of tree-level matrix elements in leading order perturbation theory and the generation of unweighted events on parton level. The matrix elements are computed with the program O'Mega [48] and used as input for the phase space integration. WHIZARD is able to calculate phase space integrals for $2 \rightarrow 6$ fermion processes. The second required input are parton distribution functions (PDFs) modeling the partons in the colliding protons, for this purpose WHIZARD uses the LHAPDF [49] library to access PDF sets. The generated parton level events can be written to the LHEF [50] file format, which then is used as input for the PYTHIA8 [51] event generator, which applies the parton shower and the hadronization.

6.4 Signal Event Generation

WHIZARD 2.1.1 was used for the generation of the official $W^\pm Zjj$ -EW signal event samples³ for this work because the anomalous quartic gauge couplings α_4 and α_5 are implemented. This is done through the electroweak chiral Lagrangian with the non-linear Σ field providing the electroweak symmetry breaking (cf. Section 2.2.1). Actually, this is implemented in various other event generators as well, the main reason for the choice of WHIZARD is the fact, that it is currently the only generator for this process, which utilizes the K-matrix unitarization scheme, which is described in Section 2.2.4. Events are generated according to all permitted processes that are included in the $W^\pm Zjj$ -EW definition introduced in Section 4.2 at leading order

³A set of events is called a *sample*.

perturbation theory. They are all at order six in the electroweak coupling constant α_{ew} . The strong coupling α_s is set to zero, so there are no strong couplings in the matrix elements of these events. Tau leptons are included in the generation.

6.4.1 Generation Phase Space

The phase space for the event generation is constrained by the following criteria:

- The distance between the two partons p_1, p_2 is required to be $\Delta R(p_1, p_2) > 0.4$.
- The transverse momentum $p_T(p_i)$ of the partons must be larger than 15 GeV.
- All partons and leptons have to be located within $|\eta| < 5.0$.
- The lepton transverse momentum $p_T(l_i)$ must be larger than 5 GeV.
- For all leptons a distance of $\Delta R(l_i, l_j) > 0.3$ is demanded.

These generation criteria does not match the selection criteria for the fiducial phase space introduced in Section 5.2 and are less constraining, to consider migration effects due to the parton shower, QED radiation and the detector simulation.

The events are generated with a proton center-of-mass energy $\sqrt{s} = 8$ TeV according to the 2012 data-taking period and the factorization scale μ_F and the renormalization scale μ_R are dynamically chosen to the invariant mass of the W and Z bosons $M(W, Z)$. The CT10 PDF set [52] is utilized for parton modeling, which is the current standard PDF set for ATLAS analyses. The Higgs boson is included with a mass of $M_H = 126$ GeV. PYTHIA8 is used for the parton shower, tau decays, QED radiation and hadronization. The detector simulation is performed with ATLFast-II in its default settings, i.e. ID and MS simulation with GEANT4 and calorimeter simulation with FastCaloSim.

6.4.2 Samples for Anomalous Quartic Gauge Couplings

57 samples with 50,000 events each have been generated with various combinations of $\alpha_4, \alpha_5 \in \{-2.0, -1.0, -0.8, -0.4, -0.1, 0, 0.1, 0.4, 0.8, 1.0, 2.0\}$. One of them is a SM sample with $\alpha_4 = \alpha_5 = 0$. Table 6.1 shows the generated samples with their dataset IDs (DS IDs) and the generator cross section σ_{gen} calculated by WHIZARD. For rising absolute values of the aQGCs increases σ_{gen} . The fiducial cross section $\sigma_{\text{fid}}^{\text{reco}}$ is the cross section on reconstruction level for the fiducial phase space, which is defined in Section 5.2. It can be calculated by:

$$\sigma_{\text{fid}}^{\text{reco}} = \sigma_{\text{gen}} \cdot A \cdot \varepsilon \quad (6.1)$$

with the acceptance A and the efficiency ε . The acceptance A accounts for the difference between the generation phase space and the fiducial phase space, where the

tracking and energy measurement is possible with acceptable accuracy and backgrounds are well suppressed. The efficiency ε accounts for detector effects, since the detector is not perfect not all particles will be detected correctly. Their product $A \cdot \varepsilon$ can be derived with the numbers of generated events N_{gen} , the number of events in the fiducial phase space on truth level $N_{\text{fid}}^{\text{truth}}$ and the number of events in the fiducial phase space on reconstruction level $N_{\text{fid}}^{\text{reco}}$ by:

$$\begin{aligned} A \cdot \varepsilon &= \frac{N_{\text{fid}}^{\text{truth}}}{N_{\text{gen}}} \cdot \frac{N_{\text{fid}}^{\text{reco}}}{N_{\text{fid}}^{\text{truth}}} \\ &= \frac{N_{\text{fid}}^{\text{reco}}}{N_{\text{gen}}}. \end{aligned} \tag{6.2}$$

This can be substituted in Equation 6.1 and one just needs these two numbers.

6.4.3 Next-to-Leading Order Corrections

WHIZARD is only able to generate events and calculate cross sections at leading order in the expansion of the strong and electroweak coupling, but corrections coming from higher orders, especially from QCD can be rather large. For that reason, the leading order cross section from WHIZARD is corrected for next-to-leading (NLO) effects. This is done by using the NLO QCD Monte Carlo generator VBFNLO [53], which is able to calculate the NLO cross section $\sigma_{\text{fid,SM}}^{\text{reco,NLO}}$ for the $W^\pm Zjj$ -EW SM process for the fiducial phase space. This cross section is used to determine the correction factor k :

$$k = \frac{\sigma_{\text{fid,SM}}^{\text{reco,NLO}}}{\sigma_{\text{fid,SM}}^{\text{reco}}}. \tag{6.3}$$

This factor is derived to $k = 1.108$, that means a difference between LO and NLO of 10.8%, which is non-negligible. The aQGCs are assumed not to influence the NLO correction, because it is NLO in the strong coupling, therefore the cross sections of the aQGC samples are simply scaled by the factor k :

$$\sigma_{\text{fid}}^{\text{reco,NLO}} = k \cdot \sigma_{\text{fid}}^{\text{reco,LO}} \tag{6.4}$$

Table 6.1: Signal samples generated with WHIZARD 2.1.1 for different values of α_4 and α_5 with their dataset IDs (DS IDs), their generator cross sections σ_{gen} and their fiducial cross sections on reconstruction level $\sigma_{\text{fid}}^{\text{reco,NLO}}$ scaled on next-to-leading order (see Section 6.4.3).

DS ID	α_4	α_5	$\sigma_{\text{gen}}[\text{fb}]$	$\sigma_{\text{fid}}^{\text{reco,NLO}}[\text{fb}]$	DS ID	α_4	α_5	$\sigma_{\text{gen}}[\text{fb}]$	$\sigma_{\text{fid}}^{\text{reco,NLO}}[\text{fb}]$
185631	0.0	0.0	24.74	0.39	185673	2.0	0.0	87.74	4.18
185648	0.0	0.1	25.80	0.52	185674	2.0	1.0	94.64	4.42
185632	0.0	0.4	33.30	1.07	185675	2.0	2.0	146.90	6.73
185633	0.0	0.8	48.65	1.93	185672	2.0	-1.0	103.10	4.65
185664	0.0	1.0	57.42	2.56	185671	2.0	-2.0	142.40	5.92
185665	0.0	2.0	115.80	5.47	185645	-0.1	0.0	26.16	0.53
185647	0.0	-0.1	25.93	0.51	185646	-0.1	0.1	26.43	0.56
185630	0.0	-0.4	34.60	1.08	185644	-0.1	-0.1	27.63	0.63
185629	0.0	-0.8	50.33	2.21	185626	-0.4	0.0	33.70	1.20
185663	0.0	-1.0	59.03	2.61	185627	-0.4	0.4	36.81	1.23
185662	0.0	-2.0	118.20	5.61	185628	-0.4	0.8	46.20	1.64
185650	0.1	0.0	25.73	0.52	185625	-0.4	-0.4	40.07	1.64
185651	0.1	0.1	26.88	0.60	185624	-0.4	-0.8	55.57	2.37
185649	0.1	-0.1	26.29	0.52	185621	-0.8	0.0	46.17	1.95
185636	0.4	0.0	32.60	1.06	185622	-0.8	0.4	48.57	2.05
185637	0.4	0.4	38.46	1.48	185623	-0.8	0.8	57.20	2.51
185638	0.4	0.8	52.94	2.47	185620	-0.8	-0.4	48.52	2.08
185635	0.4	-0.4	36.47	1.17	185619	-0.8	-0.8	62.14	2.87
185634	0.4	-0.8	46.35	1.73	185659	-1.0	0.0	52.22	2.36
185641	0.8	0.0	44.16	1.77	185660	-1.0	1.0	68.61	3.06
185642	0.8	0.4	45.88	1.91	185661	-1.0	2.0	109.50	4.40
185643	0.8	0.8	59.78	2.81	185658	-1.0	-1.0	74.75	3.66
185640	0.8	-0.4	47.65	1.98	185657	-1.0	-2.0	132.00	6.23
185639	0.8	-0.8	56.07	2.31	185654	-2.0	0.0	89.38	4.21
185668	1.0	0.0	50.35	2.35	185655	-2.0	1.0	104.40	4.71
185669	1.0	1.0	71.16	3.28	185656	-2.0	2.0	144.00	6.32
185670	1.0	2.0	127.70	6.20	185653	-2.0	-1.0	98.31	4.25
185667	1.0	-1.0	67.63	2.97	185652	-2.0	-2.0	151.90	7.07
185666	1.0	-2.0	109.90	4.45					

7 Constraints on Anomalous Quartic Electroweak Gauge Couplings

The focus of this work is on constraining the anomalous quartic electroweak gauge couplings α_4 and α_5 , which have been introduced in Chapter 2.2.3. First of all, the statistical method for obtaining upper limits is described. This method is then used to get upper limits for α_4 and α_5 with the observed and expected event yields in the fiducial phase space. These limits serve as a reference for a subsequent phase space optimization with the aim of getting more constraining upper limits. The optimization is performed by iteratively applying additional rectangular phase space cuts on aQGC sensitive kinematic distributions and determine the new upper limits.

7.1 Statistical Method

The notation is based on [54]. The probability for observing n_c^{obs} events in a *counting experiment* with theoretically predicted $s_c(\boldsymbol{\alpha}, \boldsymbol{\theta})$ signal events and $b_c(\boldsymbol{\theta}) = \sum_i b_{c,i}(\boldsymbol{\theta})$ background events for i different backgrounds is given by the Poissonian distribution:

$$\text{Pois}(n_c^{\text{obs}} | s_c(\boldsymbol{\alpha}, \boldsymbol{\theta}) + b_c(\boldsymbol{\theta})) = \frac{(s_c(\boldsymbol{\alpha}, \boldsymbol{\theta}) + b_c(\boldsymbol{\theta}))^{n_c^{\text{obs}}}}{n_c^{\text{obs}}!} e^{-(s_c(\boldsymbol{\alpha}, \boldsymbol{\theta}) + b_c(\boldsymbol{\theta}))}. \quad (7.1)$$

The index c denotes a special final state, also referred to as *channel*. As introduced in Chapter 4.2 the possible channels are: $c \in \{\text{eee}, \text{eem}, \text{mme}, \text{mmm}\}$. $\boldsymbol{\alpha}$ is used as a shortcut for $\{\alpha_4, \alpha_5\}$ and $\boldsymbol{\theta} = \{\theta_j\}$ is a set of *nuisance parameter*, which are related to the j different types of systematic uncertainties. They are unknown but constrained by $\pm 1\sigma$ variations of the sources of the systematic uncertainty j . Gaussian distributions are used to model the nuisance parameters:

$$\text{Gaus}(\theta_j^0 | \theta_j, 1) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(\theta_j^0 - \theta_j)^2}{2}}. \quad (7.2)$$

With Equations 7.1, 7.2 a likelihood function is created:

$$L(\boldsymbol{\alpha}, \boldsymbol{\theta}) = \prod_c \text{Pois}(n_c^{\text{obs}} | s_c(\boldsymbol{\alpha}, \boldsymbol{\theta}) + b_c(\boldsymbol{\theta})) \prod_j \text{Gaus}(\theta_j^0 | \theta_j, 1) \quad (7.3)$$

Using L , one can build a *profile likelihood ratio* [55]:

$$\lambda(\boldsymbol{\alpha}) = \frac{L(\boldsymbol{\alpha}, \hat{\boldsymbol{\theta}})}{L(\hat{\boldsymbol{\alpha}}, \hat{\boldsymbol{\theta}})}. \quad (7.4)$$

The name comes from the fact, that this ratio no longer depends on the nuisance parameters $\boldsymbol{\theta}$, i.e. the dependence has been “profiled out”. The numerator represents the maximized likelihood function in dependence of $\boldsymbol{\alpha}$ with the *conditional maximum likelihood estimator* $\hat{\boldsymbol{\theta}}$, while the denominator represents the global maximum of the likelihood function with the unconditional maximum likelihood estimators $\hat{\boldsymbol{\alpha}}$ and $\hat{\boldsymbol{\theta}}$. $\lambda(\boldsymbol{\alpha})$ can take all values between 0 and 1.

The signal cross section $\sigma_{\text{fid}}^{\text{reco,NLO}}$, which has been defined in Equation 6.4, is not known as an analytical function of $\boldsymbol{\alpha}$. For this reason, the profile likelihood ratio is calculated with $\sigma_{\text{fid}}^{\text{reco,NLO}}(\boldsymbol{\alpha})$ for each point in the α_4, α_5 -plane:

$$\lambda(\boldsymbol{\alpha}) = \frac{L(\sigma_{\text{fid}}^{\text{reco,NLO}}(\boldsymbol{\alpha}), \hat{\boldsymbol{\theta}})}{L(\hat{\sigma}_{\text{fid}}^{\text{reco,NLO}}, \hat{\boldsymbol{\theta}})}. \quad (7.5)$$

The cross section for each point in the α_4, α_5 -plane is determined by using the NLO fiducial cross sections on reconstruction level of the generated samples and do a bilinear interpolation. The result is shown in Figure 7.1. The evaluation of λ can be done with the cross section, because the expected number of signal events $s_c(\boldsymbol{\alpha})$, which is the only $\boldsymbol{\alpha}$ dependent quantity, is defined as:

$$s_c(\boldsymbol{\alpha}) = \sigma_{\text{fid}}^{\text{reco,NLO}}(\boldsymbol{\alpha}) \cdot \mathcal{L}_{\text{int}} \cdot \text{Br}, \quad (7.6)$$

with the integrated luminosity $\mathcal{L}_{\text{int}}$, which amounts to 20.281 fb^{-1} for the 2012 data and the *branching ratio* Br for each channel c . Due to *lepton universality* [56] each of the 4 channels has the same probability of occurrence. This is expressed in $\text{Br} = 0.25$.

A test statistic $t(\boldsymbol{\alpha})$ is defined by:

$$t(\boldsymbol{\alpha}) = \begin{cases} 0 & : \hat{\sigma}_{\text{fid}}^{\text{reco,NLO}}(\boldsymbol{\alpha}) < \sigma_{\text{fid}}^{\text{reco,NLO}}(\boldsymbol{\alpha} = 0) \\ -2 \ln \lambda(\boldsymbol{\alpha}) & : \text{otherwise.} \end{cases} \quad (7.7)$$

With $t(\boldsymbol{\alpha})$ constraints on α_4 and α_5 can be determined. The first case ensures, that the cross section $\hat{\sigma}_{\text{fid}}$ can not be smaller than the SM cross section, because the SM is assumed to be true. The Wilks theorem [57] in combination with the Wald approximation [58] states, that $t(\boldsymbol{\alpha})$ follows for n parameters of interest asymptotically a χ^2 -distribution with n degrees of freedom. In this case, the $t(\boldsymbol{\alpha})$ follows a χ^2 -distribution with $n = 1$, with the fiducial cross section σ_{fid} as parameter of interest.

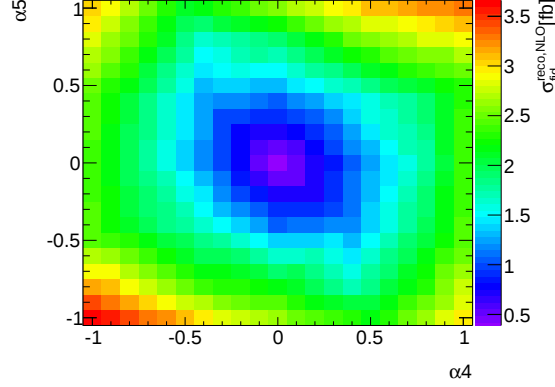


Figure 7.1: Fiducial cross section in dependance of α_4 and α_5 . Here, the fiducial cross sections of the 57 generated WHIZARD samples have been used to do a bilinear interpolation.

Thus the upper-limits for a given confidence level (CL)¹ can be obtained with the corresponding quantile of the χ^2 -distribution:

$$\text{CL} = 68\% : \chi^2 = 0.99$$

$$\text{CL} = 95\% : \chi^2 = 3.84$$

The procedure for constructing the 95% confidence region is the following:

- Search all points (α_4, α_5) with $t(\alpha) = 3.84$.
- These points result in a contour, which is the border of the confidence region. Points with higher values for $t(\alpha)$ are excluded with 95% CL.

Figure 7.2a shows the test statistic for the fiducial phase space with the *expected* 95% confidential region. For the expected case one uses the expected number of events n^{exp} instead of the observed n^{obs} in Equation 7.3. The expected number of events is given by an artificial so-called *Asimov data set*. This data set is defined by the mean expected number of the simulated events for the SM case². Especially when optimizing constraints, n^{exp} is used to avoid an optimization according to statistical fluctuations of the data. Figure 7.2b shows the expected confidence region for 95% CL and the observed confidence regions for 68% CL and 95% CL. The observed upper limits are worse than the expected, that is because more events have been observed than expected for the fiducial region, as shown in Table 7.2. The expected

¹The confidence level (CL) defines the fraction of estimated intervals from an ensemble of experiments, which covers the true value.

²The complete SM is defined as background, when constraining aQGCs.

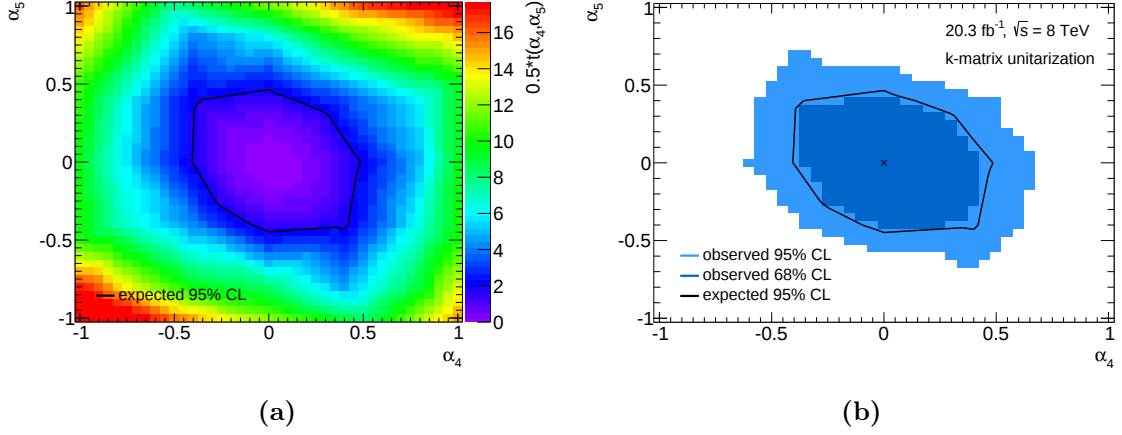


Figure 7.2: The test statistic $t(\alpha)$ in dependence of (α_4, α_5) for the fiducial phase space. The black contour marks the 95% confidence region, i.e. the values of α_4 and α_5 outside of the contour are excluded with 95% CL (a). Plot (b) shows the expected confidence region for 95% CL and observed confidence regions for 95% CL and 68% CL.

and observed upper limits for α_4 and α_5 are given in Table 7.1. The quoted limits are the limits in the first quadrant of the α_4, α_5 -plane at the intersections of the confidence region contour lines with the axes, i.e. the limit for α_4 is given for $\alpha_5 = 0$ and vice versa.

Table 7.1: Expected and observed upper limits α_4^{UL} and α_5^{UL} for the fiducial phase space.

	α_4^{UL}	α_5^{UL}
expected	0.49	0.47
observed	0.70	0.64

7.2 Systematic Uncertainties

The systematic uncertainties of the simulated events are included in the statistical method through the nuisance parameter. They can be divided into the following 3 categories:

- systematic uncertainty of the integrated luminosity,
- theory uncertainties of the event generation and

Table 7.2: Expected and observed event yield for the fiducial phase space with statistical and systematic uncertainties. The numbers are the sums of the 4 channels. More events than expected have been observed.

Process	Event yield	
$W^\pm Zjj$ -EW	10.73 ± 0.21	$^{+1.02}_{-1.49}$
$W^\pm Zjj$ -QCD	25.30 ± 0.96	$^{+5.42}_{-4.40}$
ZZ	1.96 ± 0.34	$^{+0.34}_{-0.53}$
$t\bar{t}V$	1.66 ± 0.09	$^{+0.50}_{-0.50}$
$t\bar{t}$	1.01 ± 0.57	$^{+0.43}_{-0.17}$
Z +Jets	0.95 ± 0.67	$^{+0.01}_{-0.01}$
$Z\gamma$	0.14 ± 0.14	$^{+0.55}_{-0.34}$
total expected	41.39 ± 1.37	$^{5.59}_{4.72}$
observed	45	

- systematic uncertainties of the correction factors for the simulated events (cf. Chapter 6.2).

The luminosity uncertainty has been derived to a relative uncertainty of 2.8% [59]. It is the same for all simulated event samples.

The theory uncertainties comprise the uncertainties due to not considered higher QCD orders, the uncertainty of the used parton distribution function (PDF) in the event simulation as well as the uncertainties of the used factorization and renormalization scales and the parton shower uncertainties.

As mentioned in Chapter 6.2 the simulated events need to be corrected to fit to the measured data. These corrections have a finite precision, which results in systematic uncertainties. Their impact is derived by varying the correction factors within their $\pm 1\sigma$ uncertainties and comparing the event yields to the nominal event yields. These systematic uncertainties are re-evaluated for every phase space cut in the below optimization. The considered uncertainties are:

- electron energy scale uncertainty (ElEScale),
- electron energy resolution uncertainty (ElESmear),
- electron identification (ElID), isolation (ElIso) and reconstruction (ElReco) scale factor uncertainties,
- electron trigger efficiency uncertainty (ElTrigger),

- jet energy scale (JES) and jet energy resolution (JER) uncertainties,
- E_T^{miss} uncertainty,
- muon identification scale factor uncertainty (MuID) and
- muon p_T scale, resolution and trigger efficiency uncertainty (MuPt).

All evaluated systematic uncertainties for the fiducial phase space are shown in Table 7.3 for the various samples. The total uncertainty is derived by assuming no correlation between the different uncertainties and adding them in quadrature. Additionally, the statistic uncertainty of each sample is given in the last line.

Table 7.3: Systematic Uncertainties of the various MC samples for the fiducial phase space. The used abbreviations are elucidated in the text. The total uncertainties are derived by adding the different uncertainties in quadrature.

	$W^\pm Zjj\text{-EW}$	$W^\pm Zjj\text{-QCD}$	ZZ	$t\bar{t}V$	$Z+\text{Jets}$	$Z\gamma$	$t\bar{t}$
ElEScale	+0.1/-0.6	+0.0/-0.5	+0.2/-3.5	+0.0/-0.6	+0.0/-0.0	+0.0/-0.0	+0.0/-0.0
ElESmear	+0.0/-0.2	+0.0/-0.1	+0.3/-0.0	+0.0/-0.1	+0.0/-0.0	+0.0/-0.0	+0.0/-0.0
ElID	+1.2/-1.2	+1.1/-1.1	+1.6/-1.6	+1.1/-1.1	+1.1/-1.1	+1.5/-1.5	+1.9/-1.9
ElIso	+0.3/-0.3	+0.3/-0.3	+0.3/-0.3	+0.2/-0.2	+0.2/-0.2	+0.3/-0.3	+0.4/-0.4
ElReco	+0.5/-0.5	+0.4/-0.4	+0.6/-0.6	+0.4/-0.4	+0.5/-0.5	+0.7/-0.7	+0.6/-0.6
ElTrigger	+0.0/-0.0	+0.0/-0.0	+0.0/-0.0	+0.0/-0.0	+0.0/-0.0	+0.0/-0.0	+0.2/-0.2
JER	+0.1/-0.0	+3.5/-0.0	+7.4/-0.0	+0.4/-0.0	+0.0/-0.0	+0.0/-100.0	+26.7/-0.0
JES	+3.8/-2.7	+10.0/-9.0	+2.6/-15.2	+3.9/-3.8	+0.0/-0.0	+396.5/-223.6	+33.0/-17.1
E_T^{miss}	+0.2/-0.1	+0.2/-0.0	+0.2/-0.0	+0.4/-0.2	+0.0/-0.0	+0.0/-0.0	+0.0/-0.0
MuID	+0.7/-0.7	+0.7/-0.7	+0.6/-0.6	+0.7/-0.7	+0.6/-0.6	+0.9/-0.9	+0.6/-0.6
MuPt	+0.2/-0.2	+0.3/-0.4	+0.2/-0.1	+0.0/-0.4	+0.0/-0.3	+0.0/-0.0	+0.1/-0.0
Luminosity	+2.8/-2.8	+2.8/-2.8	+2.8/-2.8	+2.8/-2.8	+2.8/-2.8	+2.8/-2.8	+2.8/-2.8
Theory	+8.6/-13.5	+18.6/-14.8	+15.1/-22.3	+30.0/-30.0	+0.0/-0.0	+0.0/-0.0	+0.0/-0.0
total	+9.5/-13.9	+21.4/-17.4	+17.1/-27.3	+30.3/-30.3	+1.4/-1.4	+396.5/-245.0	+42.6/-17.2
MC stat	± 1.9	± 3.8	± 17.5	± 5.4	± 70.7	± 100.0	± 56.8

7.3 aQGC Sensitive Variables

For an optimization of the aQGC measurement, one has to find kinematic variables that are sensitive to α_4 and α_5 . This has been done by comparing the shapes of their distributions for the $W^\pm Zjj\text{-EW}$ SM case ($\alpha_4 = \alpha_5 = 0$) to distributions with additional aQGCs. The most promising variables, that has been found are:

- $\sum |p_T^l|$: This variable is defined as the sum of the absolute transverse momenta of the 3 charged leptons in the final state:

$$\sum |p_T^l| = |p_T(l_1)| + |p_T(l_2)| + |p_T(l_3)|. \quad (7.8)$$

- $|\Delta\phi_{WZ}|$: This variable represents the angular distance of the four-momenta of the W and the Z boson in the transverse plane. To determine that the transverse four-momenta of W and Z are required. The transverse momentum of the Z boson is reconstructed by summing up the transverse four-momenta of the 2 leptons, which are the candidates to originate from it. For the W 's transverse momentum, the p_T of the third lepton and the missing transverse momentum p_T^{miss} are used for the reconstruction.

Their differential distributions for $W^\pm Zjj$ -EW are shown in the left column of Figure 7.3 for various values of (α_4, α_5) . These distributions are made with RIVET [60] on truth level for the fiducial phase space. The detector effects are not expected to strongly change the shapes in a different manner for different coupling strengths. The histograms for various coupling strengths are scaled to their corresponding cross section.

The right column shows the distribution of the expected event yields of the backgrounds. These yields are determined on reconstruction level for the fiducial phase space. The shapes of the distributions of the left and right column are comparable, since they have the same binning, they only differ in a constant scale factor, which is composed of the integrated luminosity $\mathcal{L}_{\text{int}} = 20.281 \text{ fb}^{-1}$ and the bin width of the left plots.

The comparison of the $\sum |p_T^l|$ distributions for different coupling strengths shows, that the maximum is shifted to higher values for increasing coupling parameters and the tail decreases less exponentially. The background distribution shows essentially the same behaviour like the SM case. It is dominated by the $W^\pm Zjj$ -QCD background. On the right end of the distribution an overflow bin is present.

The shape comparison of the $|\Delta\phi_{WZ}|$ distributions shows a peak at π for distributions with anomalous couplings, while the SM distribution is nearly flat and shows only a slight increase for higher values. The reason for that behaviour is an increasing correlation between the W and the Z boson for distributions with aQGCs and hence a higher probability for the bosons to be back-to-back. The background distribution shows also only a slight increase for higher values of $|\Delta\phi_{WZ}|$, but that is insignificant compared to the increase with aQGCs.

7.4 Optimization

With the two sensitive variables $\sum |p_T^l|$ and $|\Delta\phi_{WZ}|$ a two-dimensional optimization is performed. In addition to the fiducial phase space selection criteria, 2 new criteria are introduced:

- $\sum |p_T^l| > x$ with $x \in \{0, 50, 100, 150, 200, 250, 300, 350, 400, 450\} \text{ GeV}$
- $|\Delta\phi_{WZ}| > y$ with $y \in \{0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6\}$

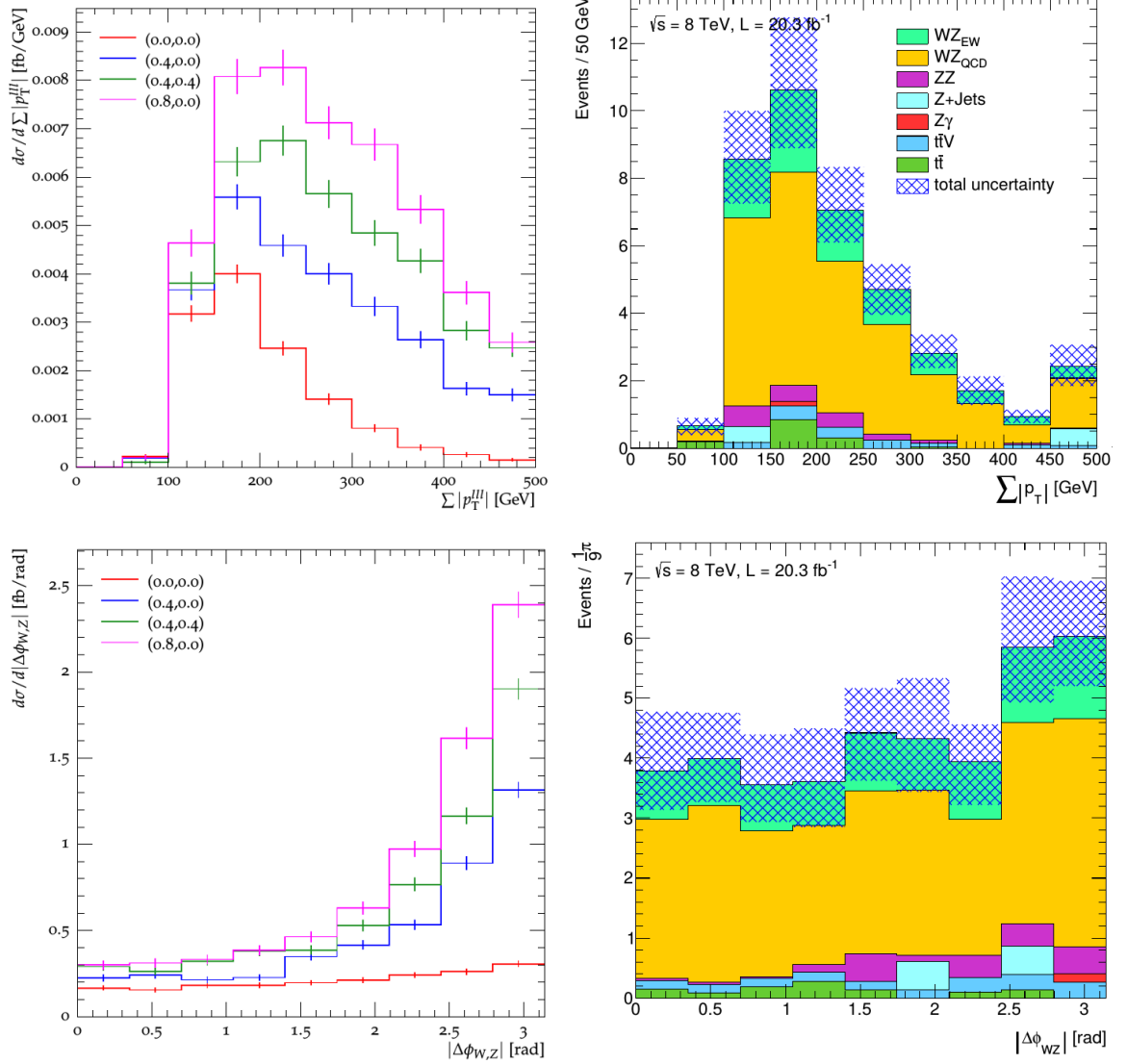


Figure 7.3: Kinematic distributions of aQGC sensitive variables. The left column shows the $\sum |p_T^l|$ and the $|\Delta\phi_{WZ}|$ distributions for different values of α_4 and α_5 on truth level. The histograms are scaled to their corresponding cross section. The right column shows the distribution of the expected event yields of the background samples for the two variables, with the total (stat+sys) uncertainties.

For every possible combination of these 2 criteria the following steps are performed:

1. Determine the signal cross section $\sigma_{\text{opt}}^{\text{reco,NLO}}$ ³ in dependence of (α_4, α_5) .
2. Re-evaluate the systematic uncertainties and the expected number of background events for the new phase space.
3. Construct the likelihood function with the Asimov data set and maximize it to remove the nuisance parameter dependence and determine the likelihood ratio $\lambda(\alpha_4, \alpha_5)$.
4. Use the test statistic $t(\alpha_4, \alpha_5) = -2 \ln \lambda(\alpha_4, \alpha_5)$ to derive the expected 95% CL upper limits for α_4 and α_5 .

Table 7.4: Expected and observed upper limits of α_4 and α_5 for the optimized phase space together with the optimal selection criteria. The observed limits are less constraining than the expected. The reason is an excess in data, which is shown in Table 7.5.

	$\sum p_T^l $ [GeV]	$ \Delta\phi_{WZ} $	α_4^{UL}	α_5^{UL}
expected	> 250	> 2.0	0.29	0.30
observed			0.53	0.52

The results of this procedure in dependence of the 2 sensitive variables are shown in Figure 7.4. The best expected upper limits for α_4 and α_5 can be read off these plots together with the optimal selection criteria. The upper limits around the optimum have been scanned with a finer step width, but the limits could not be further improved. The best expected upper limits and the corresponding selection criteria are summarized in Table 7.4 together with the observed upper limits for the optimized phase space. The observed upper limits are less constraining than the expected, due to the fact, that an excess in data is observed with respect to the expectation, which is shown in Table 7.5. This excess can be observed in Figure 7.5, there the data and the SM expectation are plotted for the 2 sensitive variables with all cuts for the optimized phase space applied, except for the one of the plotted variable. The excess is also the reason for an 68% CL exclusion of the SM point ($\alpha_4 = \alpha_5 = 0$) in Figure 7.6, which shows the expected and observed confidence regions for the optimized phase space.

³The index “opt” signalizes, that this is no longer the fiducial phase space, but the optimization phase space with the additional selection criteria.

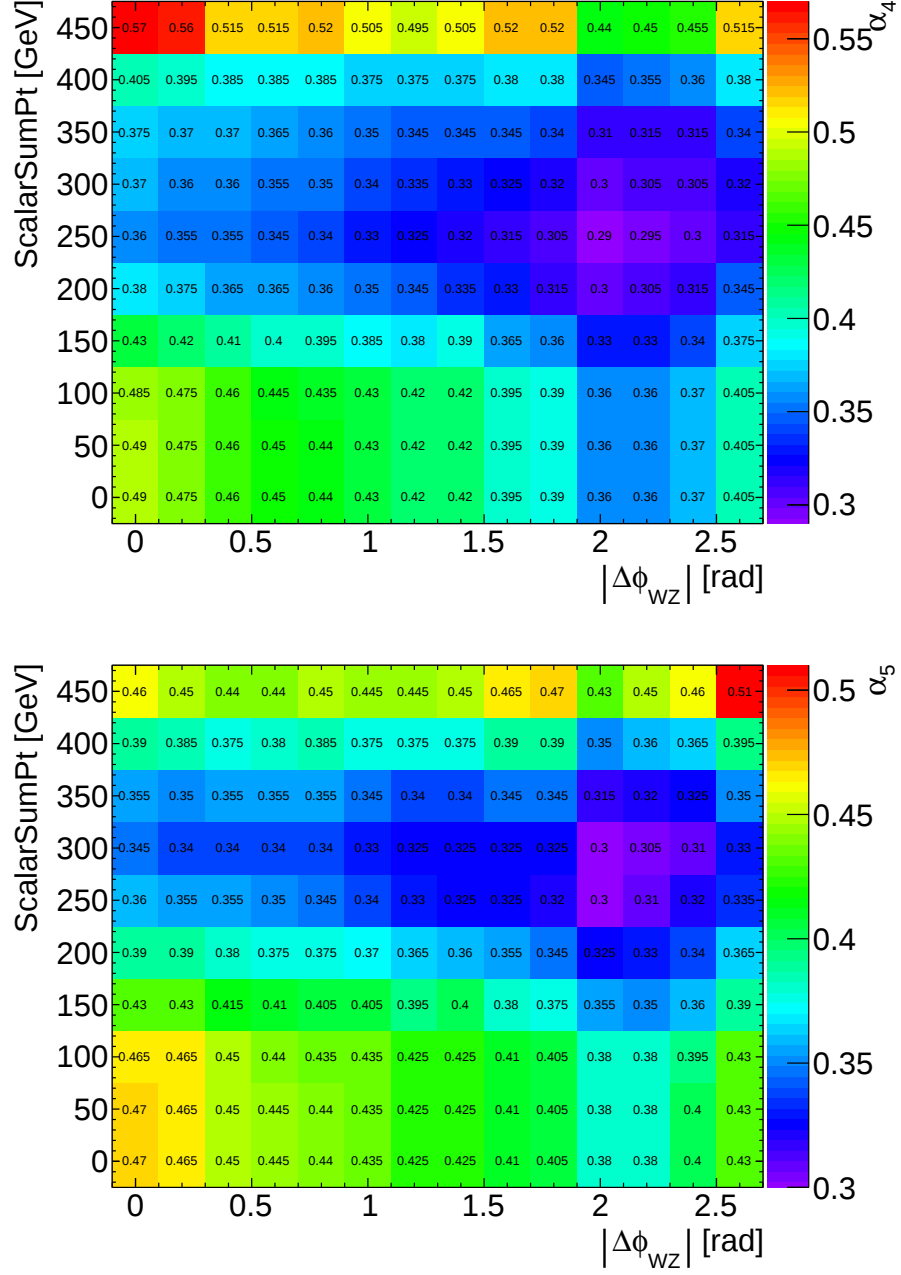


Figure 7.4: The upper limits of α_4 (top) and α_5 (bottom) in dependence of the applied cuts on $\sum |p_T^l|$ (ScalarSumPt) and $|\Delta\phi_{WZ}|$. Both plots have their optimum at $\sum |p_T^l| > 250$ GeV and $|\Delta\phi_{WZ}| > 2.0$.

Table 7.5: Expected event yield and observed data for the optimized phase space with statistical and systematic uncertainties. No events are expected from Z +Jets and $Z\gamma$. The reason for this is probably the insufficient modeling of these *fake backgrounds* with MC samples (cf. Chapter 4.3).

Process	Event yield	
$W^\pm Zjj$ -EW	1.52 ± 0.08	$^{+0.15}_{-0.23}$
$W^\pm Zjj$ -QCD	3.42 ± 0.35	$^{+0.65}_{-0.54}$
ZZ	0.25 ± 0.11	$^{+0.04}_{-0.30}$
$t\bar{t}V$	0.32 ± 0.04	$^{+0.12}_{-0.10}$
Z +Jets	0.00	
$Z\gamma$	0.00	
$t\bar{t}$	0.03 ± 0.03	$^{+0.05}_{-0.00}$
total expected	5.54 ± 0.38	$^{+0.68}_{-0.67}$
observed	9	

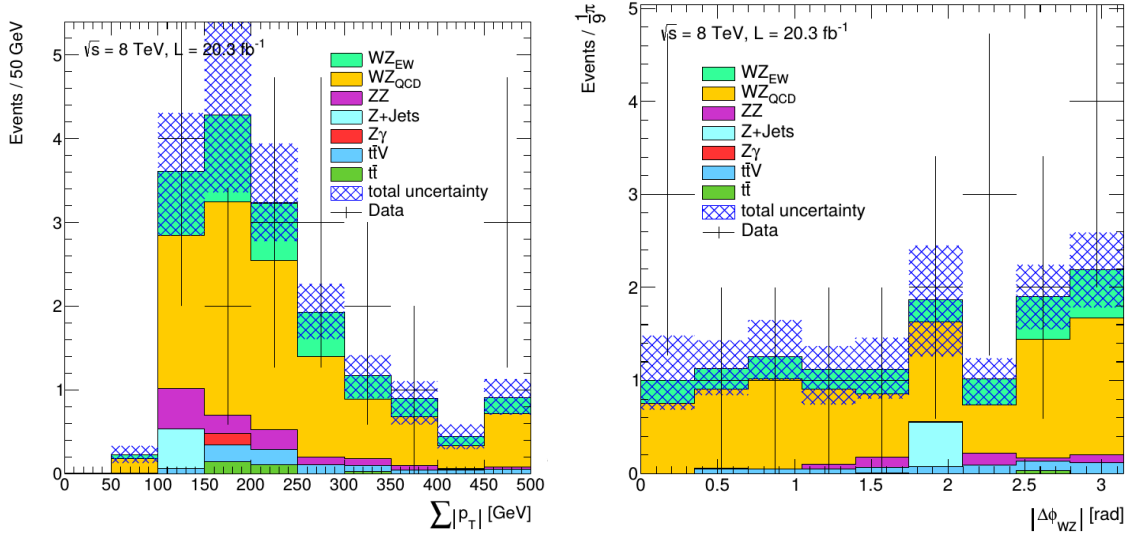


Figure 7.5: Distributions of $\sum |p_T^l|$ and $|\Delta\phi_{WZ}|$ with data. All phase space cuts for the optimized phase space are applied to the shown distributions except for the cut on the variable itself. The excess in data is clearly observable for $\sum |p_T^l| > 250$ GeV and $|\Delta\phi_{WZ}| > 2.0$

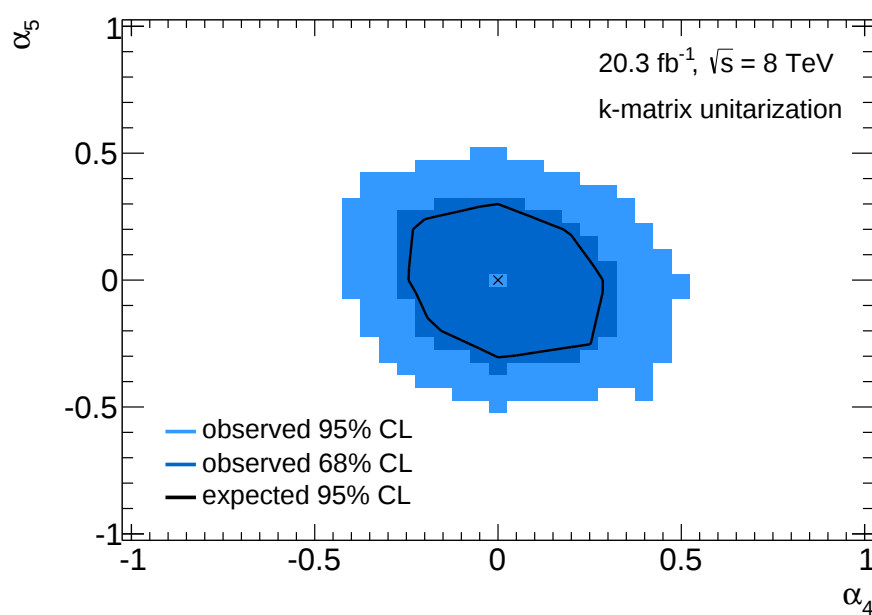


Figure 7.6: Expected and observed confidence regions for the optimized phase space. $\alpha_4 = \alpha_5 = 0$ is excluded with 68% CL for the observed case, due to an excess in data with respect to the SM expectation.

8 Conclusion

In this work the electroweak gauge boson scattering final state $W^\pm Z jj$ has been analysed with the emphasis on the anomalous quartic gauge couplings (aQGCs) α_4 and α_5 . They are introduced by an effective field theory and parametrize possible low energy effects of theories beyond the Standard Model in a model independent manner.

In a first step it was possible to constrain α_4 and α_5 in a fiducial phase space, which has not been optimized for the best sensitivity for aQGCs. The expected one-dimensional upper limits at 95% CL are:

$$\begin{aligned}\alpha_4 &\leq 0.49 \quad \text{and} \\ \alpha_5 &\leq 0.47.\end{aligned}$$

Due to a slight excess in data compared to the Standard Model prediction, the observed limits at 95% CL are less constraining. They are:

$$\begin{aligned}\alpha_4 &\leq 0.70 \quad \text{and} \\ \alpha_5 &\leq 0.64.\end{aligned}$$

The sensitivity for aQGCs has been improved with additional selection criteria. Additional phase space cuts on the scalar sum of the transverse momenta of the 3 charged leptons $\sum |p_T^l|$ and the angular distance of $W^\pm$ and Z boson four-momenta in the transverse plane $|\Delta\phi_{WZ}|$ have been applied:

$$\begin{aligned}\sum |p_T^l| &> 250 \text{ GeV} \quad \text{and} \\ |\Delta\phi_{WZ}| &> 2.0.\end{aligned}$$

In this new phase space the expected upper limits at 95% CL are improved to:

$$\begin{aligned}\alpha_4 &\leq 0.29 \quad \text{and} \\ \alpha_5 &\leq 0.30.\end{aligned}$$

This corresponds to an improvement of 59% for α_4 and 64% for α_5 . The observed upper limits are still worse with:

$$\begin{aligned}\alpha_4 &\leq 0.53 \quad \text{and} \\ \alpha_5 &\leq 0.52,\end{aligned}$$

due to an excess in data.

The aQGCs α_4 and α_5 have been already constrained in [61] with the electroweak gauge boson scattering final state $W^\pm W^\pm jj$. The expected upper limits at 95% CL of α_4 and α_5 for an optimized phase space are determined to $\alpha_4 \leq 0.04$ and $\alpha_5 \leq 0.09$ in that work. The here presented results are not competitive to these limits, but a combination could possibly result in improved constraints for the (α_4, α_5) parameter space.

A Mathematical Utilities

A.1 Pauli and Dirac Matrices

The Pauli matrices are 3 complex, hermitian and unitary 2×2 matrices, namely:

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (\text{A.1})$$

They have the following algebraic properties ($i, j, k \in \{1, 2, 3\}$):

$$\sigma_i^2 = i \sigma_1 \sigma_2 \sigma_3 = \mathbb{1}_2, \quad (\text{A.2})$$

$$\det(\sigma_i) = -1, \quad (\text{A.3})$$

$$\text{Tr}(\sigma_i) = 0, \quad (\text{A.4})$$

$$[\sigma_i, \sigma_j] = 2i \varepsilon_{ijk} \sigma_k, \quad (\text{A.5})$$

$$\{\sigma_i, \sigma_j\} = 2\delta_{ij} \mathbb{1}_2 \quad (\text{A.6})$$

with the commutator $[a, b] = ab - ba$, the anti-commutator $\{a, b\} = ab + ba$, the Levi-Civita symbol ε_{ijk} , the Kronecker delta δ_{ij} and the $n \times n$ identity matrix $\mathbb{1}_n$.

The Dirac matrices are defined by the following anti-commutation relation:

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu} \mathbb{1}_4. \quad (\text{A.7})$$

$g^{\mu\nu}$ are the components of the metric tensor of the Minkowski space, which is defined as $g^{\mu\nu} = \text{diag}(1, -1, -1, -1)$. One possible representation of the Dirac matrices (expressed with the Pauli matrices) is:

$$\gamma^0 = \begin{pmatrix} \mathbb{1}_2 & \\ & -\mathbb{1}_2 \end{pmatrix}, \quad \gamma^i = \begin{pmatrix} & \sigma_i \\ -\sigma_i & \end{pmatrix}, \quad \gamma^5 = i \gamma^0 \gamma^1 \gamma^2 \gamma^3 = \begin{pmatrix} & \mathbb{1}_2 \\ \mathbb{1}_2 & \end{pmatrix} \quad (\text{A.8})$$

The Dirac matrices have the following algebraic properties:

$$\gamma^{\mu\dagger} = \gamma^0 \gamma^\mu \gamma^0, \quad (\text{A.9})$$

$$\gamma^{5\dagger} = \gamma^5, \quad (\text{A.10})$$

$$\{\gamma^\mu, \gamma^5\} = 0, \quad (\text{A.11})$$

$$(\gamma^5)^2 = \gamma^5. \quad (\text{A.12})$$

A.2 Chirality Projection

A fermion field ψ can be decomposed into fields with a left and right chirality $\psi_{R/L}$. One has $\psi = \psi_L + \psi_R$. ψ is projected by the operator $P_{R/L}$ into its left- and right-chiral fields:

$$P_{R/L} = \frac{1}{2} (\mathbb{1}_4 \pm \gamma^5) . \quad (\text{A.13})$$

$P_{R/L}$ fulfills the following rules:

$$P_R + P_L = \mathbb{1}_4, \quad (\text{A.14})$$

$$P_R P_L = P_L P_R = 0, \quad (\text{A.15})$$

$$P_R^2 = P_R, \quad (\text{A.16})$$

$$P_L^2 = P_L \quad (\text{A.17})$$

B Monte Carlo Samples and Recorded Data

Table B.1: Data recorded with ATLAS in 2012 for $\sqrt{s} = 8$ TeV. These data sets are used to obtain the observed upper limits for α_4 and α_5 .

Period	Stream	Tag
A	Egamma	grp14_v01_p1328_p1329
B	Egamma	grp14_v01_p1328_p1329
C	Egamma	grp14_v01_p1328_p1329
D	Egamma	grp14_v01_p1328_p1329
E	Egamma	grp14_v01_p1328_p1329
G	Egamma	grp14_v01_p1328_p1329
H	Egamma	grp14_v01_p1328_p1329
I	Egamma	grp14_v01_p1328_p1329
J	Egamma	grp14_v01_p1328_p1329
L	Egamma	grp14_v01_p1328_p1329
A	Muons	grp14_v01_p1328_p1329
B	Muons	grp14_v01_p1328_p1329
C	Muons	grp14_v01_p1328_p1329
D	Muons	grp14_v01_p1328_p1329
E	Muons	grp14_v01_p1328_p1329
G	Muons	grp14_v01_p1328_p1329
H	Muons	grp14_v01_p1328_p1329
I	Muons	grp14_v01_p1328_p1329
J	Muons	grp14_v01_p1328_p1329
L	Muons	grp14_v01_p1328_p1329

Table B.2: $W^\pm Zjj$ MC samples.

DS ID	Process	Generator	Events	k-factor	σ [pb]
185396	$W^\pm Zjj$ -EW	SHERPA	269760	1	0.0821
185397	$W^\pm Zjj$ -QCD	SHERPA	1999996	1.35	9.757

Table B.3: $t\bar{t}$ and $t\bar{t}V$ MC background samples.

DS ID	Process	Generator	Events	k-factor	σ [pb]
110001	$t\bar{t}$	MC@NLO	9988449	1.2177	21.81
119353	$t\bar{t}W$	MADGRAPH	399997	1.18	0.1041
119355	$t\bar{t}Z$	MADGRAPH	399996	1.34	0.06769
174830	$t\bar{t}Wj$	MADGRAPH	399896	1.17	0.053372
174831	$t\bar{t}Wjj$	MADGRAPH	399798	1.17	0.041482
174832	$t\bar{t}Zj$	MADGRAPH	399995	1.35	0.041482
174833	$t\bar{t}Zjj$	MADGRAPH	399798	1.35	0.039772

Table B.4: ZZ MC background samples.

DS ID	Process	Generator	Events	k-factor	σ [pb]
147196	$ZZjj$ -EW	SHERPA	187599	1	0.00691
126894	ZZ	SHERPA	3799491	1	8.7403

Table B.5: Z +jets MC background samples.

DS ID	Process	Generator	Events	k-factor	σ [pb]
147770	$Z(e^+e^-)$ +jets	SHERPA	29993053	1	1241.2
147771	$Z(\mu^+\mu^-)$ +jets	SHERPA	29989732	1	1241.2

Table B.6: $Z\gamma$ MC background samples.

DS ID	Process	Generator	Events	k-factor	σ [pb]
145161	$Z(e^+e^-)\gamma$	SHERPA	8844673	1	32.26
145162	$Z(\mu^+\mu^-)\gamma$	SHERPA	9198579	1	32.317

List of Figures

2.1	Feynman diagrams of the muon decay	12
2.2	K-matrix unitarization scheme	16
3.1	Schematic view of the CERN accelerator complex	18
3.2	Cut-away view of the ATLAS Detector	20
3.3	Profile of the Inner Detector	22
3.4	Overview of the ATLAS calorimeter system	23
3.5	Schematic structure of the Electromagnetic Calorimeter	24
3.6	Profile of the Muon Spectrometer	25
4.1	Feynman diagram for electroweak gauge boson scattering	30
4.2	Feynman diagrams of electroweak gauge boson interactions	30
4.3	Feynman diagrams included in the $VVjj$ -EW definition	31
4.4	Feynman diagrams of $VVjj$ -QCD	31
5.1	Jet Vertex Fraction	37
7.1	Fiducial cross section in dependance of α_4 and α_5	49
7.2	Test statistic in dependence of (α_4, α_5) for the fiducial phase space . .	50
7.3	Kinematic distributions of aQGC sensitive variables	54
7.4	2D optimization of the upper limits of α_4 and α_5	56
7.5	Distributions of $\sum p_T^l $ and $ \Delta\phi_{WZ} $ with data	57
7.6	Expected and observed confidence regions for the optimized phase space	58

List of Tables

2.1	Fermions of the Standard Model	4
2.2	Bosons of the Standard Model	5
2.3	Fermion doublet and singlet fields of the Standard Model	7
6.1	Signal samples generated with WHIZARD 2.1.1	45
7.1	Expected and observed upper limits for α_4 and α_5 in the fiducial region	50
7.2	Expected and observed event yield for the fiducial phase space	51
7.3	Systematic Uncertainties for the fiducial phase space	52
7.4	Expected and observed 95% CL upper limits of α_4 and α_5 for the optimized phase space	55
7.5	Expected event yield and observed data for the optimized phase space	57
B.1	Data recorded by ATLAS in 2012	63
B.2	$W^\pm Zjj$ MC samples.	64
B.3	$t\bar{t}$ and $t\bar{t}V$ MC background samples.	64
B.4	ZZ MC background samples.	64
B.5	Z +jets MC background samples.	64
B.6	$Z\gamma$ MC background samples.	64

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