

**TECHNISCHE
UNIVERSITÄT
DRESDEN**

Optimization of the Search for Contributions of Anomalous Quartic Gauge Couplings to Vector Boson Scattering at the Large Hadron Collider

Diplomarbeit
zur Erlangung des wissenschaftlichen Grades
Diplom-Physiker

vorgelegt von

Constanze Hasterok
geboren am 27.09.1988 in Dresden

CERN-THESIS-2013-273
14/11/2013



TECHNISCHE UNIVERSITÄT DRESDEN
INSTITUT FÜR KERN- UND TEILCHENPHYSIK
FACHRICHTUNG PHYSIK
FAKULTÄT FÜR MATHEMATIK UND NATURWISSENSCHAFTEN
2013

Eingereicht am 29.10.2013

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

Kurzdarstellung

Mit der Higgs-Boson-Entdeckung wurde eine weitere Vorhersage des Standard Modells bestätigt. Dennoch gibt es Phänomene, die im Rahmen dieses Modells nicht erklärt werden können. Daher wird angenommen, dass das Standard Modell eine niederenergetische Näherung einer komplexeren Theorie ist.

Effekte dieser neuen Theorie könnten schon im Niedrigenergiebereich sichtbar sein und können mittels des Ansatzes effektiver Feldtheorien durch anomale Kopplungsparameter, α_4 und α_5 , parametrisiert werden.

In dieser Arbeit werden, ausgehend vom Wirkungsquerschnitt der Streuung zweier gleich geladener W Bosonen, Grenzen auf anomale Kopplungen des Vier-Eichbosonen-Vertex bestimmt. Schnitte auf verschiedene kinematische Variablen werden hinsichtlich ihrer Sensitivität auf die Anwesenheit von anomalen Vier-Eichkopplungen (aQGC) optimiert. Als Grundlage dient der Datensatz von Proton-Proton-Kollisionen aufgezeichnet mit dem ATLAS Detektor im Jahr 2012 bei einer Schwerpunktenenergie von $\sqrt{s} = 8$ TeV und einer integrierten Luminosität von $\int L dt = 20,3 \text{ fb}^{-1}$.

Die optimierte Ereignisselektion führt zu erwarteten eindimensionalen oberen Grenzen von 0,04 für α_4 und 0,09 für α_5 bei einem Vertrauensniveau von 95%. Aufgrund des beobachteten Defizits in den Daten im ausgewählten Phasenraum ergeben sich leicht strengere Einschränkungen von 0,02 für α_4 und 0,04 für α_5 .

Abstract

With the discovery of the Higgs boson a further prediction of the Standard Model has been confirmed. However, some phenomenons can not be explained within this model. Therefore, it is assumed that the Standard Model is a low energy approximation of a more complex theory.

Effects of this new theory could be visible in the low energy region. They can be parametrized within an effective field theory approach by anomalous coupling parameters α_4 and α_5 .

In this work, based on the cross section measurement of the scattering of two equally signed W bosons constraints are set on anomalous couplings in the quartic gauge boson vertex. Cuts on various kinematic variables are optimized with the focus on their sensitivity to the presence of anomalous quartic gauge couplings (aQGC). The data set of proton-proton-collisions recorded with the ATLAS detector in 2012 at a center of mass energy of $\sqrt{s} = 8$ TeV and an integrated luminosity of $\int L dt = 20.3 \text{ fb}^{-1}$ is used in this analysis.

The optimized event selection results in expected one dimensional upper bounds of 0.04 for α_4 and 0.09 for α_5 at 95% confidence level. Due to an observed deficit in the selected phase space, slightly stronger constraints of 0.02 for α_4 and 0.04 in α_5 are obtained.

Contents

1	Introduction	1
2	Theoretical Foundations	3
2.1	The Standard Model of Particle Physics	3
2.1.1	Particles	3
2.1.2	Forces	4
2.1.3	Electroweak Theory	6
2.1.4	Electroweak symmetry breaking	8
2.2	Effective Field Theories	10
2.3	Anomalous Quartic Gauge Couplings	12
2.3.1	Electroweak Chiral Lagrangian	12
2.3.2	Operators of aQGC	14
2.3.3	Interference between Standard Model and aQGC	15
2.4	K-Matrix Unitarization	16
3	The ATLAS Experiment	19
3.1	Large Hadron Collider	19
3.1.1	Technical Details	19
3.1.2	The Large Hadron Collider Experiments	21
3.2	The ATLAS Detector	21
3.2.1	Detector Coordinate System	22
3.2.2	Inner Detector	23
3.2.3	Calorimeter System	24
3.2.4	Muon System	25
3.2.5	Forward Detectors	26
3.2.6	Trigger and Data Acquisition System	27
4	Object Reconstruction in ATLAS	29
4.1	Triggers	29
4.2	Primary Vertex	29
4.3	Muons	29
4.4	Electrons	30
4.5	Jets	30
4.6	Missing Transverse Energy	32
4.7	Resolving Ambiguities	32

4.8	Pile-Up	33
5	Monte Carlo Event Generation	35
5.1	Event Generation Procedure	35
5.2	Corrections to Simulated Events	37
5.3	The Event Generator WHIZARD	38
6	Vector Boson Scattering	39
6.1	Motivation of Observing Vector Boson Scattering	39
6.2	Topology	40
6.3	Classification of Vector Boson Scattering Processes	41
7	Measurement of aQGC in $W^\pm W^\pm$ Scattering	43
7.1	The $W^\pm W^\pm jj$ Process	43
7.1.1	Topology	44
7.1.2	Background Processes	45
7.2	Object and Event Selection	50
7.2.1	Object Selection	50
7.2.2	Event Selection	52
7.3	Cross Section Extraction	53
7.4	Systematic Uncertainties	54
7.5	Results of Cross Section Measurement	56
7.6	Signal Samples and Cross Sections	57
7.6.1	Official WHIZARD Signal Samples	57
7.6.2	Cross Sections of aQGC Scenarios	58
7.6.3	Exclusion of aQGC Cross Sections	61
7.7	Variables Sensitive to aQGC	61
7.8	Statistical Analysis	68
7.8.1	Profile Likelihood Method	68
7.8.2	The Likelihood Function	69
7.9	Measurement of aQGC	70
7.9.1	Procedure	71
7.9.2	Results	71
7.10	Cut optimization	72
7.10.1	Optimization Setup	73
7.10.2	Results	74
7.11	Discussion and Conclusions	81
8	Conclusion	83
A	WZ-Analysis	85
A.1	Introduction	85
A.2	Background Processes	86
A.3	Object and Event Selection	87
A.3.1	Electron and Muon Selection	87
A.3.2	Event Selection	88

A.4	Isolation Studies	88
A.4.1	Lepton Isolation Variables	88
A.4.2	Optimization of Lepton Isolation	90
A.4.3	Conclusions	92
A.5	Studies on Lepton Systematic Uncertainties	93
A.5.1	Muon Systematic Uncertainties	93
A.5.2	Electron Systematic Uncertainties	94
A.5.3	Discussion	94
B	Mathematical Utilities	97
B.1	Correlation Coefficient of random variables	97
B.2	Bilinear Interpolation	97
C	Measurement of aQGC in $W^\pm W^\pm$ Scattering	99
C.1	Monte Carlo Background Samples	99
C.2	Event Cleaning cuts	103
C.3	Object Definitions	103
C.3.1	Muons	103
C.3.2	Electrons	103
C.3.3	Tag Electron Definition in the Tag-and-Probe Method	103
C.3.4	Jets	104
C.4	Overview of Optimizations	104

Chapter 1

Introduction

The Standard Model is the theoretical fundament of modern particle physics and all its aspects have been investigated and are in good agreement with the observation. Recently, the last fundamental building block of the Standard Model's spectrum of particles was found. In 2012, a new SM Higgs boson like particle was discovered [1, 2]. This lead to the Nobel Prize of Physics which was awarded to the founders of the electroweak symmetry breaking mechanism of the Standard Model called the Higgs mechanism: Francois Englert and Peter Higgs.

The Standard Model is now complete and one of the best tested theories. However, there are open questions the Standard Model cannot solve yet. Some of them are:

- How can gravitation be included into the Standard Model as a quantum field theory?
- What are dark matter and dark energy?
- Where do the values of the Yukawa couplings come from?

Three energy scales are defined by the three most characteristic quantities of the fundamental forces, the proton mass m_p , the Fermi constant G_F and Newton's constant G_N . The scale of the proton mass is characteristic for strong interactions, the Fermi scale for electroweak interactions and the Planck scale for gravitational interactions:

$$\begin{array}{lll} \text{Proton mass:} & m_p & \approx 1 \text{ GeV} \\ \text{Fermi scale:} & v = (\sqrt{2}G_F)^{-1/2} & \approx 246 \text{ GeV} \\ \text{Planck scale:} & M_{Planck} = G_N^{-1/2} & \approx 1.22 \times 10^{19} \text{ GeV} \end{array}$$

The characteristic scales of $r = m_p^{-1}$ and $r = v^{-1}$ can in principle be reached by extrapolating the corresponding renormalizable quantum field theories and also collider experiments provide insight into these scales. However, a quantum field theory breaks down at the Planck scale not speaking of reachability by experiments. Unlike the other two scales it seems that the Planck scale sets a fundamental limit.

From this point of view one more fundamental question arises:

Is the Standard Model still valid at energy scales far beyond the Fermi scale or does in this region a new theory enter which may explain the questions above?

This can only be answered by building high energy colliders that extend the borders of experimentally accessible energies. The Large Hadron Collider (LHC) at CERN in Geneva provides the possibility to discover such new physics with its unprecedented energy and the high luminosity.

The scattering of massive gauge bosons is well suited to search for new physics since it is very sensitive to the electroweak symmetry breaking mechanism. Though the Higgs mechanism was recently confirmed it could still differ from the predictions in the Standard Model. In some theories the Higgs boson is a composite particle which results in resonances that contribute to the electroweak symmetry breaking. The corresponding effects will become stronger with increasing energy.

New physics that may occur at not yet reached energies can be described by an effective approach where the Standard Model is considered as a low-energy effective theory. This way anomalous couplings are introduced into the Lagrangian as new degrees of freedom parameterizing effects from new physics on the electroweak sector. They modify the vertices of vector boson scattering.

For the first time the quartic vertex of the scattering of two massive vector bosons is measured in the production channel of two equally charged W bosons by the ATLAS experiment at the LHC. Hence, anomalous quartic gauge couplings (aQGC) of massive bosons have not yet been determined.

Therefore, the goal of this thesis is constraining the parameter space of anomalous quartic gauge couplings by measuring the cross section of vector boson scattering with the 2012 ATLAS data ($\sqrt{s} = 8$ TeV, $\int L dt = 20$ fb $^{-1}$). The sensitivity of some kinematic variables to aQGC is studied and an optimization of the event selection by setting rectangular cuts on aQGC sensitive variables is conducted. This way, the constraints on the aQGC parameters are tightened.

Throughout this work only leptonic final states are investigated whose advantage is the very clean signature and reconstruction by ATLAS. In the example of the production of a W and a Z boson which is the dominant background of the scattering of two equally charged W bosons, the systematic uncertainties resulting from the lepton reconstruction and lepton isolation requirements are studied.

This thesis is structured as follows: The theoretical framework of the Standard Model with the focus on the electroweak sector is described in Chapter 2. The experimental setup with the LHC and the ATLAS detector is briefly reviewed in Chapter 3. In Chapter 4, the reconstruction of the signatures of physical objects and in Chapter 5 the generation of simulated data by Monte Carlo techniques are outlined. Chapter 6 reviews the event topology of vector boson scattering in general and in Chapter 7 the scattering process of two equally charged W bosons is analyzed. This chapter includes the measurement of aQGC and the optimization of the event selection. The conclusions of the work are discussed in Chapter 8.

Chapter 2

Theoretical Foundations

2.1 The Standard Model of Particle Physics

The Standard Model of particle physics (SM) is the experimentally best tested quantum field theory. It describes the properties of the fundamental particles and their interactions and is in good agreement with the currently available experimental data.

In the following, a brief overview on the theory shall be given with the focus on the electroweak sector. A more detailed description can be found in various specialist literature [3, 4, 5].

2.1.1 Particles

According to the SM the elementary particles are classified into *bosons* and *fermions* depending on their spin.

Fermions have half-integer spin and follow the Fermi-Dirac statistics. They are distinguished into two types, *leptons* and *quarks*. Leptons carry an electrical charge of 0 or ± 1 . One elementary negative charge have the electron e^- , the muon μ^- , and the tau τ^- . Their anti-particles' electrical charges have opposite sign and are called positron e^+ , anti-muon μ^+ , and anti-tau τ^+ . The associated electrically neutral particles are the electron-neutrino ν_e , the muon-neutrino ν_μ , the tau-neutrino ν_τ and their corresponding antiparticles $\bar{\nu}_e$, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$.

Quarks are electrically charged with $+\frac{2}{3}$ or $-\frac{1}{3}$. There are in total 12 quark types, also referred to as *flavours*, 6 particles and 6 antiparticles. The up and down quarks, u and d , are the building blocks of hadrons like the proton and neutron and hence, contribute to the matter we know from everyday life. The charm, strange, top and bottom quarks, c , s , t , and b , are only virtually existent in hadrons due to fluctuations of gluons into quarks and anti-quarks or are produced in collisions.

All fermions can be grouped into three generations whereas within one generation all particles act the same under symmetry transformations. The symmetry groups of the Standard Model will be explained in Section 2.1.2. The only differences between particles in one generation are their masses.

Table 2.1 gives an overview on all known fermions.

Generation	Fermion	Electric Charge	Mass [MeV ¹]
1 st	e^-	electron	-1
	ν_e	electron-neutrino	0
	u	up-quark	+2/3
	d	down-quark	-1/3
2 nd	μ^-	muon	-1
	ν_μ	muon-neutrino	0
	c	charm-quark	+2/3
	s	strange-quark	-1/3
3 rd	τ^-	tau	-1
	ν_τ	tau-neutrino	0
	t	top-quark	+2/3
	b	bottom-quark	-1/3

Table 2.1: Overview of the Standard Model fermions with their electric charges and their experimental masses [6].

Bosons have integer spin and follow the laws of Bose-Einstein statistics. In the local gauge theory, which will be explained in section 2.1.3, most of the Standard Model bosons are introduced in order to ensure local gauge symmetry. They are also referred to as *gauge bosons*, have a spin of one and act as mediators of forces. Those are the massless photon γ , the massless gluons g and the massive bosons W^+ , W^- and Z . Bosons with a mass and a spin of one are also called *vector bosons* since the spin operator has three eigenstates and therefore, three degrees of freedom like a vector in the three dimensional space. For massless bosons only spins parallel or anti-parallel to the direction of motion are allowed [7].

In contrast to the force carriers stands the Higgs boson which is not associated to a force but is an excitation of the Higgs field and has spin 0. The Higgs field is one possibility to break the electroweak symmetry of the Standard Model and thus give mass to the gauge bosons W^+ , W^- and Z and the fermions. This mechanism will be explained in Section 2.1.4.

The properties of the Standard Model bosons are listed in Table 2.2.

2.1.2 Forces

As far as our present knowledge goes, there are four fundamental types of interactions: the electromagnetic force, the strong force, the weak force and the gravitational force. The first

¹In particle physics natural units are commonly used where $c = \hbar = 1$. This convention is applied throughout this work.

²deduced from the kinematics of tritium decays

³Due to confinement, the single quark masses can be estimated only. They are deduced using a mass-independent subtraction scheme such as $\overline{MS}$. μ indicates the renormalization scale on which the masses have been normalized.

⁴deduced from the kinematics of pion decays

⁵deduced from the kinematics of three and five prong tau decays

⁶direct measurement

Boson		Mass [GeV]	Electric Charge	Spin
Photon	γ	$< 10^{-27}$	0	1
W bosons	$W^\pm$	80.385 ± 0.015	± 1	1
Z bosons	Z	91.1876 ± 0.0021	0	1
Gluons	g	0 (from theory) ⁷	0	1
Higgs boson	H	> 115.5 not 127-600 (95% CL)	0	0

Table 2.2: Summary of the Standard Model bosons, their masses, electric charges and spins [6].

three of them are part of the Standard Model whereas the gravitational force can not yet be described by a quantum field theory.

Electrically charged particles are influenced by the electromagnetic force in exchanging photons. The corresponding processes are described by Quantum Electrodynamics (QED) [9]. The weak force has three massive force carriers, W^+ , W^- , and Z , and acts on all left handed fermions. The strong force is mediated by gluons which couple to color charged particles. Only quarks and the gluons themselves are color charged. Their interactions are described by Quantum Chromodynamics (QCD) [10, 11, 12, 13].

Each force is associated to a symmetry group whose operators take the particle charges⁸ as eigenvalues (quantum numbers). Particles that are charged under a certain symmetry group can interact with each other by exchanging the corresponding gauge boson. The symmetry group of the Standard Model is given by:

$$U(1)_{Y_W} \otimes SU(2)_L \otimes SU(3)_c \quad (2.1)$$

The indices c and Y_W indicate the quantum numbers of the $SU(3)$ and $U(1)$ symmetry groups. They stand for color and the weak hypercharge respectively. The index L indicates that only left chiral (left handed) fermions transform under the $SU(2)$ group. A gauge field can be associated to each generator of a symmetry group which gives rise to a gauge boson. Table 2.3 lists the Standard Model symmetry groups and their corresponding gauge field and bosons. The $SU(3)_c$ is the symmetry group of the strong force and $U(1)_{Y_W} \otimes SU(2)_L$ is the combination of the electromagnetic and the weak force referred to as electroweak force. It is described in the Glashow-Weinberg-Salam (GWS) theory [14, 15, 16].

Up to now the gravitational force is well described by Einstein's general theory of relativity [17] but cannot yet be included in any quantum field theory. However, there are many efforts and new ideas to combine the SM forces with the gravitation at high energies. This theory is called grand unified theory (GUT) [18, 19].

⁷A mass as large as a few MeV is not ruled out [8]

⁸The term "charge" does not only include the electrical charge which is often the naive association. In quantum field theory, charges are eigenvalues of transformation operators of a symmetry group.

Symmetry Group	Gauge Field	Gauge Boson
$SU(3)_c$	G_μ^a	8 gluons
$SU(2)_L$	W_μ^a	$\left. \vphantom{\begin{matrix} \gamma, W, Z \end{matrix}} \right\} \gamma, W, Z$
$U(1)_{Y_W}$	B_μ	

Table 2.3: Summary of the Standard Model symmetry groups and their associated gauge fields and bosons.

Leptons						
	$j = 1$	$j = 2$	$j = 3$	Q	T_3^W	Y_W
$L_L^j \left\{ \begin{array}{l} \nu_{e,L} \\ e_L \end{array} \right.$	$\nu_{e,L}$	$\nu_{\mu,L}$	$\nu_{\tau,L}$	0	+1/2	-1/2
	e_L	μ_L	τ_L	-1	-1/2	-1/2
l_R^j	e_R	μ_R	τ_R	-1	0	-1

Quarks						
	$j = 1$	$j = 2$	$j = 3$	Q	T_3	Y_W
$Q_L^j \left\{ \begin{array}{l} u_L \\ d'_L \end{array} \right.$	u_L	c_L	t_L	+2/3	+1/2	+1/6
	d'_L	s'_L	b'_L	-1/3	-1/2	+1/6
u_R^j	u_R	c_R	t_R	+2/3	0	+2/3
d'^j_R	d'_R	s'_R	b'_R	-1/3	0	-1/3

Table 2.4: Summary of fermions fields with their associated quantum numbers in the electroweak symmetry groups. The index j stands for the generations and the apostrophe at the down type quarks denotes the weak eigenstates that can be transformed to the mass eigenstates by the CKM matrix [20, 21].

2.1.3 Electroweak Theory

Since the focus of this work lies on vector boson scattering, its underlying theory, the electroweak theory, shall be discussed in more detail in the following.

Fermion fields can be separated into left handed and right handed contributions when applying the projection operator:

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

where γ^5 is the product of the four Dirac matrices and the imaginary number i . Hence, a fermion field can be written as

$$\Psi = P_L \Psi + P_R \Psi = \Psi^L + \Psi^R. \quad (2.3)$$

Left handed leptons and quarks are classified into doublets, L_L^j and Q_L^j , of the third component T_3 of the weak isospin $\vec{T}$ which is the charge associated to the $SU(2)_L$ symmetry group. Right handed fermions are grouped into singlets, l_R^j , u_R^j and d'^j_R , of T_3 since they do

not transform under $SU(2)_L$ transformations and $\vec{T} = \vec{0}$ for those. Left handed neutrinos have $T_3 = 1/2$ and left handed electrons, muons, and taus have $T_3 = -1/2$. Right handed neutrinos are either expected to be either a non-coupling part of our light Dirac neutrinos or form additional sterile neutrinos, which means that they participate in the gravitational interaction only. Hence, they are candidates for dark matter [22]. Table 2.4 summarizes the fermion fields with their corresponding quantum numbers.

To conserve the symmetry of the electroweak (EW) symmetry group under local gauge transformations

$$\Psi \rightarrow e^{i(\alpha(x)Y_W + \beta_a(x)T_a)}\Psi, \quad (2.4)$$

the differential derivatives in the Lagrangian have to be replaced by covariant derivatives. This introduces the gauge fields W_μ^a and B_μ by

$$D_\mu = \partial_\mu + ig \sum_a W_\mu^a T_a + ig' B_\mu Y_W \quad (2.5)$$

with $T^a = \sigma_a/2$ being half of the Pauli matrices.

The full Lagrangian has then the form⁹:

$$\begin{aligned} \mathcal{L} = & i\bar{L}_L^j \gamma^\mu D_\mu^L L_L^j + i\bar{l}_R^j \gamma^\mu D_\mu^R l_R^j \\ & + i\bar{Q}_L^j \gamma^\mu D_\mu^L Q_L^j + i\bar{u}_R^j \gamma^\mu D_\mu^R u_R^j + i\bar{d}_R^j \gamma^\mu D_\mu^R d_R^j \\ & - \frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \end{aligned} \quad (2.6)$$

γ_μ are the four Dirac matrices. The overlined fields represent the adjoint spinors defined by

$$\bar{\Psi} \equiv \Psi^\dagger \gamma^0. \quad (2.7)$$

The first two lines in Equation 2.6 describe the kinetic terms of the fermions and their interactions with the gauge fields. The third line contains the kinetic terms and self couplings of the gauge fields. The field strength tensors $B_{\mu\nu}$ and $W_{\mu\nu}^a$ can be expressed in terms of the gauge fields as

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad \text{and} \quad (2.8)$$

$$W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g\epsilon^{abc} W_\mu^b W_\nu^c, \quad (2.9)$$

with ϵ^{abc} being the Levi-Civita-Symbol.

From the Lagrangian in Equation 2.6, the physical gauge bosons can be derived. The photon does not couple to neutrinos which is why no gauge field can be associated to the photon field A_μ . A_μ and the Z boson field Z_μ have to be linear combinations of two of the three gauge fields:

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos \Theta_W & \sin \Theta_W \\ -\sin \Theta_W & \cos \Theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}. \quad (2.10)$$

⁹Following Einstein's sum convention, the sum over the time-space index μ is suppressed. This will be done for the fermion generation index j and the index referring to the three Pauli matrices a throughout this work as well.

This corresponds to a rotation of the vector $\begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}$ by the electroweak mixing angle θ_W . θ_W is connected to the coupling constants g and g' by

$$\cos \theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \quad \text{and} \quad \sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}. \quad (2.11)$$

The physical fields of the W^+ and W^- bosons, W_μ^+ and W_μ^- , are a superposition of the gauge fields W_μ^1 and W_μ^2 :

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2). \quad (2.12)$$

In a last step a relation between the charge and the weak isospin and weak hypercharge can be derived from the coupling terms in the Lagrangian:

$$Q = T_3^W + Y_W. \quad (2.13)$$

2.1.4 Electroweak symmetry breaking

The Lagrangian in Equation 2.6 does not yet contain any mass terms. Nevertheless the gauge bosons W^+ , W^- , and Z are massive as well as the fermions. However, mass terms of the form $m\bar{\Psi}\Psi$ violate the gauge invariance. Therefore, the $SU(2)_L \otimes U(1)_{Y_W}$ symmetry has to be broken or hidden.

In order to introduce mass terms into the Lagrangian, P. Higgs et al. [23, 24] proposed a complex scalar $SU(2)$ doublet field ϕ with a weak hypercharge of $Y_W = \frac{1}{2}$. The Lagrangian of this Higgs field is given by

$$\mathcal{L}_{Higgs} = (D_\mu \phi)^\dagger (D_\mu \phi) - V(\phi) + \mathcal{L}_Y \quad (2.14)$$

$\mathcal{L}_Y$ is the Lagrangian containing Yukawa couplings between the Higgs field and the fermions which leads to the generation of the fermion masses after the spontaneous symmetry breaking. D_μ is the covariant derivative with $Y_W = \frac{1}{2}$ and $V(\phi)$ is the potential of the Higgs field which has the form

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad \text{with} \quad \mu^2, \lambda > 0. \quad (2.15)$$

μ^2 and λ are parameters that have to be determined by measurement. The Higgs doublet is given by

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + H + iG) \end{pmatrix}, \quad (2.16)$$

where the upper indices at the field components indicate the electrical charge which is deduced by applying the electrical charge operator from Equation 2.13. The fields G^+ and G are called Goldstone fields and are a complex and a scalar field respectively. H is a scalar field as well and v is the *vacuum expectation value* which is defined by the minimum of the

Higgs potential:

$$|\phi_0| = \sqrt{\frac{\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}} \quad (2.17)$$

There are several ground states possible that have the absolute value $|\phi_0|$. One possible choice is

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.18)$$

which respects the non-observation of a positive electrically charged background field ϕ^+ . The choice of a ground state with a non-zero vacuum expectation value breaks the global symmetry where the ground state would be the instable point of maximum energy, into a local symmetry. This is called *spontaneous symmetry breaking*. The term “symmetry breaking” is misleading because the $SU(2)_L \otimes U(1)_{Y_W}$ is still present in the Lagrangian but it is hidden. A gauge can now be applied in order to simplify the problem. In *unitary gauge* the three degrees of freedom of the Goldstone fields are absorbed into the longitudinal polarizations of the three massive gauge bosons and the Higgs boson H , a scalar and massive particle, results from deviations of the Higgs field from its ground state:

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

When inserting the Higgs field from Equation 2.19 into the Lagrangian from Equation 2.14, the masses of the vector bosons arise from their couplings to the Higgs field:

$$\mathcal{L}_{Higgs} = \frac{1}{2}(\partial_\mu H)^2 - \frac{1}{2}M_H^2 H^2 - \sqrt{\frac{\lambda}{2}}M_H H^3 - \frac{1}{4}\lambda H^4 \quad (2.20)$$

$$+ \left[M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}M_Z^2 Z_\mu^+ Z^\mu \right] \left(1 + \frac{H}{v} \right)^2 + \mathcal{L}_Y \quad (2.21)$$

with

$$M_W = \frac{gv}{2}, \quad (2.22)$$

$$M_Z = \frac{\sqrt{g^2 + g'^2}}{2} v, \quad \text{and} \quad (2.23)$$

$$M_H = \sqrt{2\lambda} v. \quad (2.24)$$

The vacuum expectation value takes the value [6]

$$v = 246 \text{ GeV}. \quad (2.25)$$

Electroweak symmetry breaking (EWSB) is very important in vector boson scattering since it avoids the violation of unitarity in the scattering amplitudes of massive vector bosons at high energy scales. Therefore, VBS is well suited to investigate the symmetry breaking mechanism. In the context of effective field theories a further mechanism shall be introduced in Section 2.3 which follows a more general approach.

2.2 Effective Field Theories

Though the Standard Model has proven its validity in many experiments and describes the fundamental particle physics very well, it has yet some weaknesses. The unification of the electroweak and the strong force and the explanation why there are exactly three generations of particles are only two examples. There are many new theories that describe physics beyond the Standard Model and beyond the currently experimentally accessible energies. To determine which theory above the electroweak energy scale is valid, experiments would need to set limits on the parameters of every model.

The advantage of an effective field theory is the model independence or the possibility to investigate new physics with only few assumptions. The fundamental consideration is that details from a theory that exists in a high energy limit can be neglected in experiments at lower energies. This means that in the average, microscopic effects of new physics would not be seen at macroscopic scales.

The Standard Model implicitly makes the assumption that the number of free parameters of the model is finite and therefore this theory becomes renormalizable¹⁰. The degrees of freedom in the Lagrangian build the spectrum of particles that are fundamental. However, it is not yet excluded that e.g. the Higgs boson or the weak interaction bosons are composed particles. In a fundamental quantum field the renormalizability is a crucial property. But it is not a useful principle for a description of physics beyond currently explored energy scales since in this region the number of degrees of freedom is unknown. Therefore, the only suited framework for understanding the physics that comes with these high energies is a non-renormalizable field theory with an infinite set of new observables and hence, an infinite set of possible underlying theories. This theory is required to be valid in the low energy region since we are looking for effects of the new physics in experimentally accessible regions. Therefore, all the symmetries and degrees of freedom of established theories have to be included in the Lagrangian [25].

These new physics effects can be described by operators that are added to the SM Lagrangian. Operators are defined as terms that contain fields. An effective Lagrangian contains an infinite set of operators $\mathcal{O}$ that is ordered according to their energy dimension d [26]:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_d \sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}. \quad (2.26)$$

The index i denotes different operators of the same dimension.

Since the action $S = \int d^4x \mathcal{L}$ is a dimensionless variable and d^4x has the dimension -4, the full Lagrangian has to be of dimension 4. This means that operators of dimension d have couplings of dimension $4 - d$. For operators with $d > 4$ the dimension of the coupling constant becomes negative and the renormalizability is lost. The dependence on the dimension can be absorbed into a parameter Λ which indicates the energy scale above which details of the new physics become important and the new theory is needed. This leads to dimensionless coupling constants $f_i^{(d)}$. The complete effective theory is described by an infinite set of operators but higher dimension operators are suppressed by factors of $1/\Lambda^{d-4}$.

¹⁰In a renormalized theory cross sections are not allowed to go to infinity with increasing center of mass energy.

In order to validate a new theory its parameters have to be determined by experiments. In a first step constraints can be set on them. This may also lead to an exclusion of the new theory in the case the whole parameter space is excluded.

The Fermi Theory

An illustrative example for an effective field theory is the Fermi theory which was proposed by Enrico Fermi [27]. Originally it was developed to explain the β decay but it can also be applied to the muon decay which will be used as an example in the following: $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$. When Fermi conceived the theory, the W and Z bosons were still unknown. Therefore, the interaction was described via a four fermion vertex which is shown in Figure 2.1a. The corresponding Lagrangian has the following form

$$\mathcal{L}_{Fermi} = -\frac{G_F}{\sqrt{2}} \bar{\nu}_\mu \gamma^\alpha (1 - \gamma^5) \mu \bar{e} \gamma_\alpha (1 - \gamma^5) \nu_e, \quad (2.27)$$

with $\bar{\nu}_\mu$, μ , $\bar{e}$ and ν_e being fermion fields with the energy dimension of 3/2. The operator $\mathcal{O}_F = \bar{\nu}_\mu \gamma^\alpha (1 - \gamma^5) \mu \bar{e} \gamma_\alpha (1 - \gamma^5) \nu_e$ is of energy dimension 6. Hence, the coupling constant $G_F/\sqrt{2}$ attributed to the operator has dimension -2. This indicates that the theory is not renormalizable at high energies which is also reflected in the proportionality of the cross section to the center of mass energy $\sqrt{s}$. The theory can be written in terms of the effective Lagrangian notation:

$$\mathcal{L}_{Fermi} = \frac{f_F}{\Lambda^2} \mathcal{O}_F \quad \text{with} \quad \frac{f_F}{\Lambda^2} = \frac{G_F}{\sqrt{2}}. \quad (2.28)$$

The four fermion vertex is only correct up to an energy Λ . Above this scale the unitarity of the S-matrix is violated because the mass of the W boson becomes significant and non negligible.

The problem can be solved by the GWS-Theory that was presented in Section 2.1.3. It describes the interaction with the help of the W boson that mediates the weak force between the fermions. The corresponding Feynman diagram is shown in Figure 2.1b and the Lagrangian takes the form

$$\mathcal{L}_{GWS} = -\frac{g^2}{8} \bar{\nu}_\mu \gamma^\alpha (1 - \gamma^5) \mu \frac{1}{q^2 - M_W^2} \bar{e} \gamma_\alpha (1 - \gamma^5) \nu_e. \quad (2.29)$$

The propagator of the W boson suppresses the increase of the cross section with $q^2 = s$. Hence, this theory is valid for high center of mass energies and the cross sections are finite.

The relation of the coupling constant in the GWS-Theory g to the Fermi constant G_F can be derived by expanding the boson propagator in q^2/M_W^2 :

$$\frac{1}{q^2 - M_W^2} = -\frac{1}{M_W^2} \left[1 + \frac{q^2}{M_W^2} + \dots \right]. \quad (2.30)$$

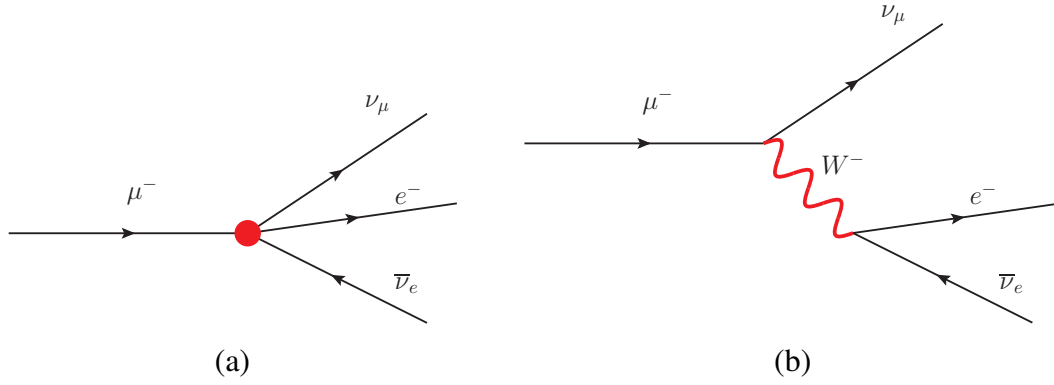


Figure 2.1: Feynman diagrams of the muon decay in the Fermi theory (a) and the Standard Model in leading order (b).

For small energies $q^2 \ll M_W^2$ this leads to

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}. \quad (2.31)$$

Comparing this equation to Equation 2.28, the scale of new physics Λ turns out to be the boson mass M_W and that the coupling constant is given by

$$f_F = \frac{g^2}{8}. \quad (2.32)$$

2.3 Anomalous Quartic Gauge Couplings

In this diploma thesis anomalous couplings in the quartic gauge boson vertex shall be investigated. They are a feature of the electroweak theory which was explained in Section 2.1.3. The study of quartic gauge couplings is very promising as a new physics search and is hardly investigated up to now. For the first time experimentally accessible energies are high enough to measure the anomalous quartic gauge coupling (aQGC) parameters in massive vector boson scattering. An effective field theory is used to introduce new coupling parameters that shall be constrained in this work.

2.3.1 Electroweak Chiral Lagrangian

As explained in Section 2.2, an effective electroweak field theory is required to have the same symmetries and degrees of freedom as the SM electroweak theory. This means that the Lagrangian is desired to be invariant under $SU(2)_L \otimes U(1)_{Y_W}$ and Lorentz transformations. In [28] a model of vector boson scattering is described. It uses a *chiral Lagrangian approach* where the electroweak symmetry breaking is realized not by a Higgs field like in the SM but by a field $\Sigma(x)$. It ensures, like the Higgs field, the gauge invariance of the fermion and boson mass terms.

The $\Sigma(x)$ field is a (2×2) matrix that transforms under $SU(2)_L \otimes U(1)_{Y_W}$ like

$$\Sigma \rightarrow U(x) \Sigma V^\dagger(x), \quad (2.33)$$

with $V(x)$ being the transformation matrix of the $U(1)$ symmetry and $U(x)$ the transformation matrix of $SU(2)$. The effective Lagrangian then has the form [25]

$$\begin{aligned} \mathcal{L}_{\text{chiral}} = & -\frac{v^2}{4} \text{tr}[V_\mu V^\mu] - \beta' \frac{v^2}{8} \text{tr}[TV_\mu] \text{tr}[TV^\mu] \\ & - (\bar{Q}_L \Sigma M_Q Q_R + \bar{L}_L \Sigma M_L L_R + h.c.) \\ & - \bar{L}_L^c \Sigma^* M_{N_L} \frac{1 + \sigma_3}{2} \Sigma L_L - \bar{L}_R^c M_{N_R} \frac{1 + \sigma_3}{2} L_R \\ & + \bar{Q}_L i \not{D} Q_L + \bar{q}_R i \not{D} Q_R + \bar{L}_L i \not{D} L_L + \bar{l}_R i \not{D} l_R \\ & - \frac{1}{2} \text{tr}[\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}] - \frac{1}{2} \text{tr}[\mathbf{B}_{\mu\nu} \mathbf{B}^{\mu\nu}] \\ & - \frac{\mu^2 v^2}{4} \text{tr}[\Sigma^\dagger \Sigma] + \frac{\lambda v^4}{16} \text{tr}[\Sigma^\dagger \Sigma]^2 + \dots \end{aligned} \quad (2.34)$$

The operators in the first line are of energy dimension 2 and represent kinetic energy terms of the Σ field with β' being a free parameter. These terms replace the boson mass terms. V_μ and T are defined as

$$V_\mu = \Sigma (D_\mu \Sigma)^\dagger \quad \text{and} \quad T = \Sigma \sigma_3 \Sigma^\dagger, \quad (2.35)$$

and the covariant derivative of the Σ field has the form

$$D_\mu \Sigma \equiv \partial_\mu \Sigma + ig \frac{\sigma_a}{2} W_\mu^a \Sigma - ig' \Sigma \frac{\sigma_3}{2} B_\mu. \quad (2.36)$$

The second and third lines in Equation 2.34 contain operators of dimension three and represent the fermion mass terms. In this notation the right handed fermions are grouped in doublets like the left handed fermions. This allows the neutrinos to have masses. The term $(1 + \sigma_3)/2$ is an operator that projects only the neutrino components of the fermion doublets. The dimension four operators of the Lagrangian in line four and five do not include the Σ field since they are invariant under electroweak symmetry transformations by themselves. These terms describe the kinematics of fermion and gauge fields.

The terms in the last line are potential terms of the Σ field. They are only needed if fluctuations of the field are allowed which implies that a particle like the Higgs boson is present.

$\mathcal{L}_{\text{chiral}}$ is referred to as *chiral Lagrangian* because left handed and right handed fermions transform independently under $SU(2)_L \otimes U(1)_{Y_W}$ transformations. Since this is a crucial feature of the electroweak theory any Lagrangian that describes electroweak interactions is chiral. However, in literature the term is often used in the context of the special Higgs-less representation of the Lagrangian.

If we assume that there are no fluctuations in the Σ field, i.e. that there is no Higgs boson, the Σ field is constrained by

$$\Sigma^\dagger \Sigma \equiv 1. \quad (2.37)$$

It forces Σ to be a unitary matrix. Such a (2×2) matrix has three degrees of freedom and therefore, Σ can be parametrized by at least three fields. There is not a unique parametrization but there are many representations. One possibility is

$$\Sigma(x) = \exp\left(\frac{-i}{v}\mathbf{w}(x)\right) \quad \text{with} \quad \mathbf{w} = \sum_{a=1}^3 w^a \boldsymbol{\sigma}^a \quad (2.38)$$

w^a are Goldstone bosons that become the longitudinal components of the vector bosons after the symmetry breaking.

The symmetry breaking is realized by choosing

$$\langle \Sigma(x) \rangle \rightarrow 1 \quad \text{for} \quad x \rightarrow \infty \quad (2.39)$$

as the ground state. The global symmetry of the Lagrangian then breaks down to a so-called *custodial symmetry* $SU(2)_{cu}$ where Σ transforms as

$$\Sigma \rightarrow C \Sigma C^\dagger \quad (2.40)$$

with $C \in SU(2)_{cu}$.

The Higgs mechanism is a special case of the EWSB by the Σ field. In this case Σ is parametrized linearly and fluctuations of the field are allowed.

The effective theory derived in this section is valid up to an energy scale of $4\pi v \simeq 3 \text{ TeV}$ [26].

2.3.2 Operators of aQGC

The effective chiral Lagrangian from Equation 2.34 is not yet complete since more dimension four operators consistent with the electroweak symmetry can be found. It can be extended by dimension four NLO EW operators with symmetric Σ -dependent terms [25]. There are eleven that are CP invariant but only five of them are symmetric under $SU(2)_{cu}$ transformations. These are

$$\mathcal{L}_1 = \alpha_1 g g' \text{tr}[\Sigma \mathbf{B}_{\mu\nu} \Sigma^\dagger \mathbf{W}^{\mu\nu}], \quad (2.41)$$

$$\mathcal{L}_2 = i\alpha_2 g' \text{tr}[\Sigma \mathbf{B}_{\mu\nu} \Sigma^\dagger [V^\mu, V^\nu]], \quad (2.42)$$

$$\mathcal{L}_3 = i\alpha_3 g \text{tr}[\mathbf{W}_{\mu\nu} [V^\mu, V^\nu]], \quad (2.43)$$

$$\mathcal{L}_4 = \alpha_4 (\text{tr}[V_\mu V_\nu])^2, \quad \text{and} \quad (2.44)$$

$$\mathcal{L}_5 = \alpha_5 (\text{tr}[V_\mu V^\mu])^2. \quad (2.45)$$

In this work, anomalous coupling parameters shall be constrained in the measurement of the scattering of two W bosons with equal electric charge. $\mathcal{L}_1$ and $\mathcal{L}_2$ modify only triple gauge couplings. Hence, they are not relevant for our process of interest. $\mathcal{L}_3$ modifies triple and quartic gauge couplings and $\mathcal{L}_4$ and $\mathcal{L}_5$ modify only quartic gauge couplings [29].

Anomalous triple gauge couplings parameters have already been constrained at FERMILAB and LEP experiments [30, 31]. However, aQGC are still unconstrained. Therefore, α_4 and

α_5 are the parameters which shall be measured in this thesis. They parametrize possible new physics and are expected to be in the order of $\alpha_i = v^2/\Lambda^2$ [29]. For $\alpha_4 = \alpha_5 = 0$ at leading order (LO), the SM is recovered.

2.3.3 Interference between Standard Model and aQGC

The cross section derived from the effective Lagrangian including aQGC parameters can be written in terms of the transition matrix of the SM driven process $\mathcal{M}_{\text{SM}}$ and the aQGC driven process $\mathcal{M}_{\text{aQGC}}$:

$$\begin{aligned} \sigma = & \alpha_i^2 \cdot \int |\mathcal{M}_{\text{aQGC}}|^2 d\Phi + \int |\mathcal{M}_{\text{SM}}|^2 d\Phi \\ & + 2\alpha_i \int (\text{Re}(\mathcal{M}_{\text{aQGC}})\text{Re}(\mathcal{M}_{\text{SM}}) + \text{Im}(\mathcal{M}_{\text{aQGC}})\text{Im}(\mathcal{M}_{\text{SM}})) d\Phi \end{aligned} \quad (2.46)$$

with α_i being either α_4 or α_5 and Φ being the phase space volume.

The interference between the SM and the aQGC process σ_{int} is expressed in the last term. It is shown in Figure 2.2 in relation to the total cross section for the electroweak production of two W^+ bosons. The interference is at maximum $\sim 2\%$ for α_4 about 0.02 and for α_5 about 0.05. It will be considered as negligible throughout this work.

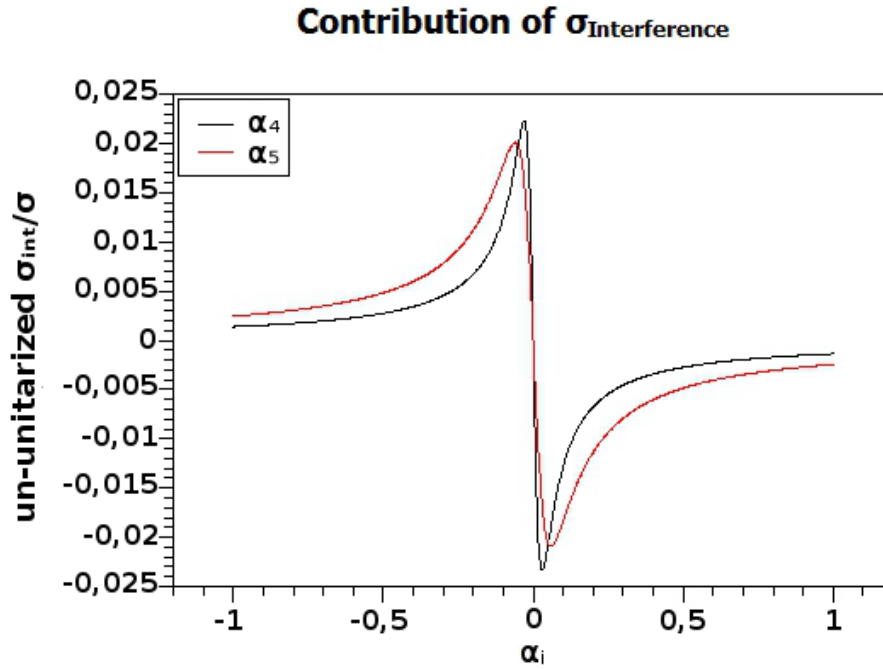


Figure 2.2: Relative interference of the SM and the aQGC cross section in dependence of α_4 and α_5 for W^+W^+ electroweak production (Graphic taken from [32]).

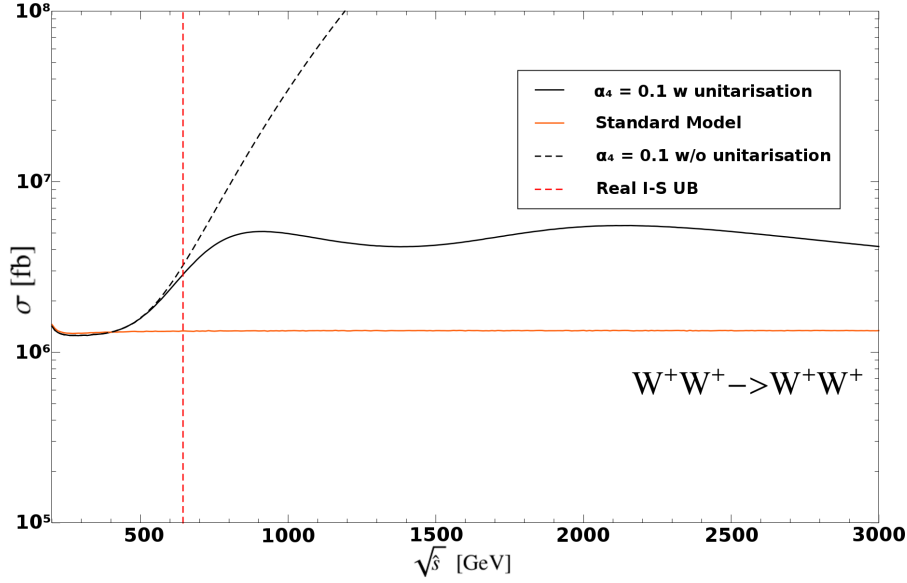


Figure 2.3: Elastic scattering cross section of two W^+ bosons over the center of mass energy. The orange line indicates the SM process, the black dashed line the aQGC scenario $\alpha_4 = 0$ and $\alpha_5 = 0.1$ as resulting from the effective Lagrangian and the black solid line the same but unitarized aQGC scenario. [33].

2.4 K-Matrix Unitarization

The additional NLO operators in the effective Lagrangian cause the rising of the scattering cross section with a power of the center of mass energy $\sqrt{s}$ for high energies. Figure 2.3 shows the cross section of the elastic scattering of two W^+ bosons over the partonic center of mass energy for the aQGC scenario $\alpha_4 = 0$ and $\alpha_5 = 0.1$ (black dashed line). In order to conserve the finiteness of the cross section, a unitarization model has to be applied which is derived in the following.

The cross section σ can be evaluated by

$$\sigma = \int f^2 d\Omega, \quad (2.47)$$

where Ω denotes the solid angle and f the scattering amplitude. The latter is directly connected to the wave functions of the initial and final state ψ_i and ψ_f :

$$f = \frac{1}{8\pi\sqrt{s}} \mathcal{M} = \langle \psi_f | S | \psi_i \rangle \quad (2.48)$$

with $\mathcal{M}$ being the transition matrix element and S the scattering matrix. The transition matrix element can be expanded into partial waves and has then the form

$$\mathcal{M}(\theta) = 32\pi \sum_l (2l+1) P_l(\cos\theta) a_l(s), \quad (2.49)$$

with $a_l = e^{i\delta_l} \sin \delta_l$ being the amplitude of the partial wave with the phase shift δ_l . In elastic scattering, a_l is real in LO. Next to leading order (NLO= corrections add imaginary parts to a_l . Inelastic scattering partial wave amplitudes are imaginary already for LO calculations. The optical theorem guarantees unitarity and is given by

$$\sigma \leq \frac{\text{Im}[\mathcal{M}(0)]}{s}. \quad (2.50)$$

By inserting 2.49 and 2.48 in 2.47 and applying 2.50 the unitarity condition for partial wave amplitudes is given by [33]

$$\sigma = \frac{1}{64\pi^2 s} \int d\Omega |\mathcal{M}|^2 \leq \frac{\text{Im}[\mathcal{M}(0)]}{s} \quad (2.51)$$

$$\sum_l \frac{32\pi(2l+1)}{s} |a_l| \leq \sum_l \frac{32\pi(2l+1)}{s} \text{Im}[a_l] \quad (2.52)$$

$$\Rightarrow |a_l|^2 \leq \text{Im}[a_l]. \quad (2.53)$$

Relation 2.53 is equivalent to

$$\left| a_l - \frac{i}{2} \right| \leq \frac{1}{2}. \quad (2.54)$$

This means that the normalized partial amplitudes stay on (elastic scattering) or in (inelastic scattering) a circle in the complex plane called *Argand-Circle*.

In this work, the focus lies on elastic scattering which is calculated at LO. The corresponding partial amplitudes are always real and therefore lie always outside the circle. Often, they rise with the center of mass energy. In order to unitarize them, the amplitudes are transformed into amplitudes on the circle $a_K(s)$. The transformation is done by

$$a_K(s) \equiv \frac{1}{\text{Re}(1/a_l(s)) - i} \quad (2.55)$$

for real amplitudes [28]. In Figure 2.4 the unitarization procedure is illustrated.

If an amplitude diverges ($a_l(s) \rightarrow \infty$), the projected amplitude $a_K(s)$ will converge to the point $0 + i$. This would correspond to an infinitely massive resonance and results in a nearly flat cross section at high energies. Figure 2.3 shows the unitarized cross section of the aQGC scenario $\alpha_4 = 0$ and $\alpha_5 = 0.1$ as a black solid line in comparison to the SM (orange solid line). The SM cross section is flat while in the aQGC case the cross section first rises and is unitarized as soon as the eigenamplitudes violate unitarity and reaches a saturation.

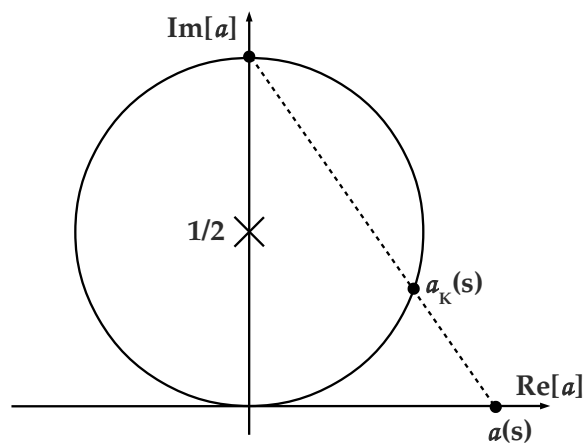


Figure 2.4: Illustration of the K-matrix unitarization method that projects any real eigenamplitude $a(s)$ that lies outside the Argand-circle onto the circle.

Chapter 3

The ATLAS Experiment

The ATLAS¹ experiment is a collaboration project with about 3000 scientists (including about 1000 graduate students) from 38 countries. The aim is to measure known physics with higher precision (e.g. Standard Model parameters) and to search for new physics like the Higgs boson and extra dimensions.

To understand how researches and measurements are done, it is advantageous to know some technical aspects of the Large Hadron Collider (LHC) which provides the ATLAS detector with high energetic particles, as well as to understand how particles emerging from the collision are measured in the ATLAS detector.

3.1 Large Hadron Collider

With its unprecedented high energy and luminosity the Large Hadron Collider (LHC) will provide insight into particle physics beyond the frontiers of former colliders. It is located near Geneva at the border between France and Switzerland.

In November 2008, the LHC started its operation. On November 23, the first proton-proton collision at a center of mass energy of 900 GeV took place. About one week later, the operation had to be closed because of a faulty electrical connection between two superconducting magnets. This led to the destruction of 53 magnets due to the evaporation of liquid helium used for the magnet cooling. After a repair period and further technical testings the first proton-proton collisions at $\sqrt{s} = 7$ TeV were recorded in March 2010. In 2012, the beam energy was increased to $\sqrt{s} = 8$ TeV and on February 14, 2013, the LHC completed its first three year run period. After a stop for technical maintenance the collider will resume its work in 2015 with an envisaged collision energy of 13 TeV and increased luminosity.

3.1.1 Technical Details

The LHC [34] is designed to collide proton bunches of up to 10^{11} particles at a center of mass energy of 14 TeV. 40 million bunch crossings per second and a design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ are envisaged. Not only protons but also heavy ions like lead ions can be

¹abbreviation for A Toroidal LH Collider ApparatuS

accelerated.

The beam pipe is situated 175 m underground in the tunnel of the former Large Electron Positron Collider (LEP) that was closed down in November 2000. The ring has a circumference of 27 km. In the proton run mode, the protons are extracted from a proton source and guided into the pre-accelerator system. This system consists of colliders which were built for former experiments. The whole accelerator complex at CERN is shown in Figure 3.1.

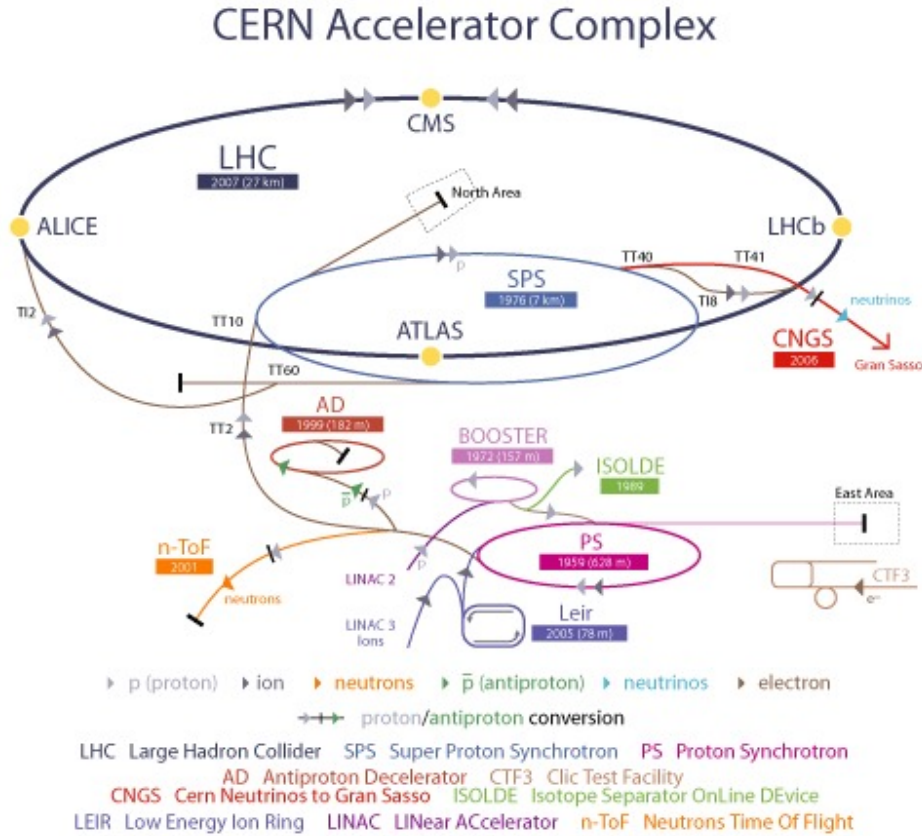


Figure 3.1: The LHC accelerator complex [35]

Protons extracted from a helium source are brought to an energy of 50 MeV by the linear accelerator LINAC 2. Afterwards they are fed into the Proton Synchrotron Booster (PSB), then into the Proton Synchrotron (PS) to reach an energy of 26 GeV and then into the Super Proton Synchrotron (SPS). Finally, when they reach an energy of 450 GeV, they are injected into the main accelerator, the LHC. Inside the beam pipe two anti-parallel beams are circulating whose energy is ramped up to a maximum design energy of 7 TeV, resulting in a center of mass energy of $\sqrt{s} = 14$ TeV.

In order to bend particles with such strong energies, high magnetic fields are necessary. They are required to have magnetic fluxes between 0.5 and 8.3 T depending on the beam energy. 1232 superconducting dipole magnets cooled by super-fluid helium to a temperature of 1.9 K are installed along the beam pipe.

Since the protons are accelerated with a frequency of 400.8 MHz no continuous beam can be technically created. Therefore the protons are separated in up to 2808 bunches per beam with a separation time of 25 ns and an average of $1.15 \cdot 10^{11}$ protons per bunch.

The rate of occurrence of a certain process can be calculated using the following formula

$$\frac{dN}{dt} = \sigma \cdot L, \quad (3.1)$$

with σ being the cross section of the process and L the instantaneous luminosity. L is a machine dependent parameter and can be adjusted to the needs of the experiment. Interesting new physics processes mainly have cross sections many orders of magnitude smaller than most Standard Model processes. Therefore, high luminosities are needed in order to be sufficiently sensitive to new physics.

3.1.2 The Large Hadron Collider Experiments

At the four crossing points of the counter rotating beams, four experiments are installed in underground caverns: ALICE [36], ATLAS [37], CMS [38] and LHCb [39] (see Figure 3.1). ALICE (A Large Ion Collider Experiment) is designed to take data mainly in the heavy ion run mode of the LHC. By colliding lead nuclei at 2.76 TeV beam energy, quark-gluon states similar to those that existed right after the Big Bang shall be constructed. Thus, the quark-gluon plasma can be explored in order to answer open questions of Quantum Chromodynamics (QCD) like the confinement of quarks or how the masses of hadrons can be predicted. The LHCb (b stands for the bottom quark) deals especially with b-quark physics and aims to measure CP violation. It may help to understand the asymmetry between matter and antimatter in the universe. The CMS (Compact Muon Solenoid) and ATLAS experiments are general purpose detectors to do research in a wide range of physics, including the Higgs boson search, the search for extra dimensions and dark matter, and the measurement of Standard Model parameters with higher precision than former experiments. The two experiments are intended to explore the same topics in order to have independent results for comparison.

3.2 The ATLAS Detector

With its aim to cover a wide range of physics, the ATLAS detector has to measure the tracks, momenta, and energies of elementary particles with high precision. Additionally, its design is optimized to detect as many particles from the collision as possible. An overview of the ATLAS detector and its sub-components is given in Figure 3.2.

The ATLAS detector consists of three overall detector systems: The *inner detector* (ID) which is situated in the center of the detector aims to reconstruct the tracks of charged particles, the *electromagnetic and hadronic calorimeters* measure the energy of charged particles and the *muon spectrometer* (MS) is constructed as the outermost sub-detector in order to measure muon momenta.

They shall be explained in more detail in the sections following the introduction of the detector coordinate system.

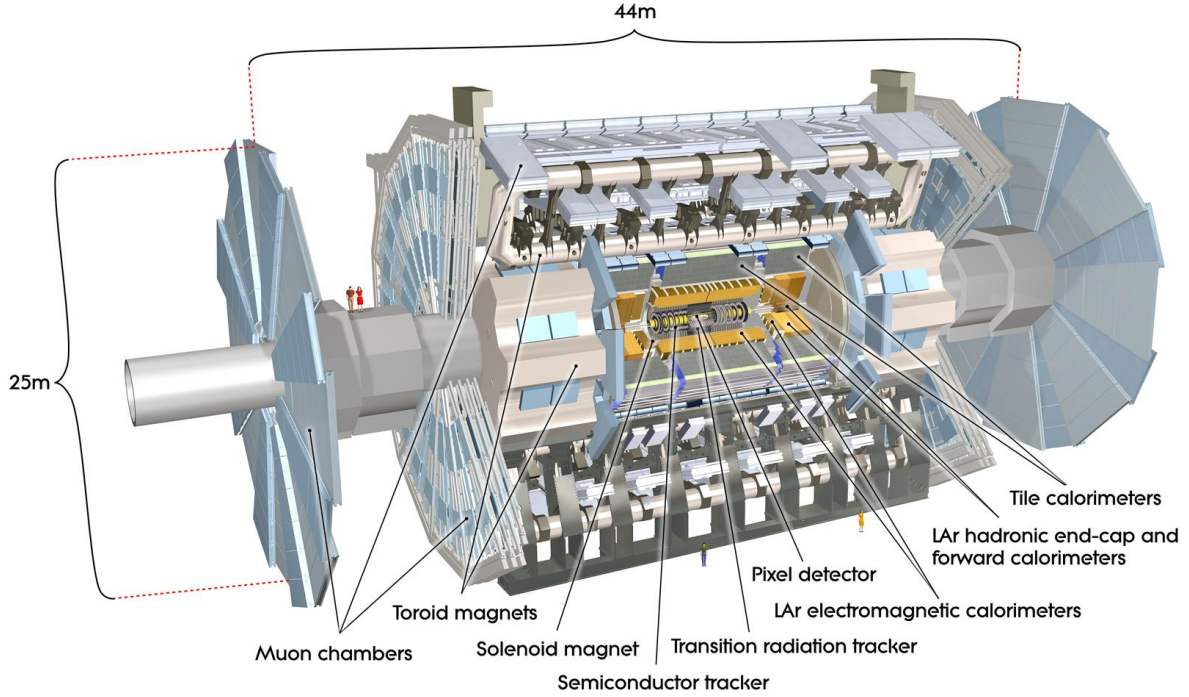


Figure 3.2: Overview of the ATLAS detector [37]

3.2.1 Detector Coordinate System

In order to be sensitive to particles nearly in the whole solid angle (4π) around the interaction point, the ATLAS detector was built as a cylinder with forward-backward symmetry. The coordinate system of ATLAS is a Cartesian right-handed coordinate system with the nominal interaction point being the origin. The z -axis is parallel to the beam axis and its positive part points into the anti-clockwise direction of the LHC ring. The x -axis is defined as pointing to the center of the LHC ring and the positive y -axis points upwards. The plane defined by the x - and y -axis is called transverse plane. The azimuthal angle ϕ is defined as a rotation around the beam axis. The polar angle θ is defined with respect to the z -axis. Transverse variables are projections onto the transverse plane and are denoted by a subscript T. In the inner detector, a magnetic field parallel to the beam direction is present. It forces charged particles on spiral tracks. The radius is given by

$$r = \frac{p_T}{B \cdot q} \quad (3.2)$$

with p_T being the transverse momentum of the particle, B being the magnetic flux density and q the absolute value of the particle charge.

In particle physics, the *rapidity* is a commonly used kinematic variable of particles. Unlike velocities it is additive in special relativity and is given by

$$Y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (3.3)$$

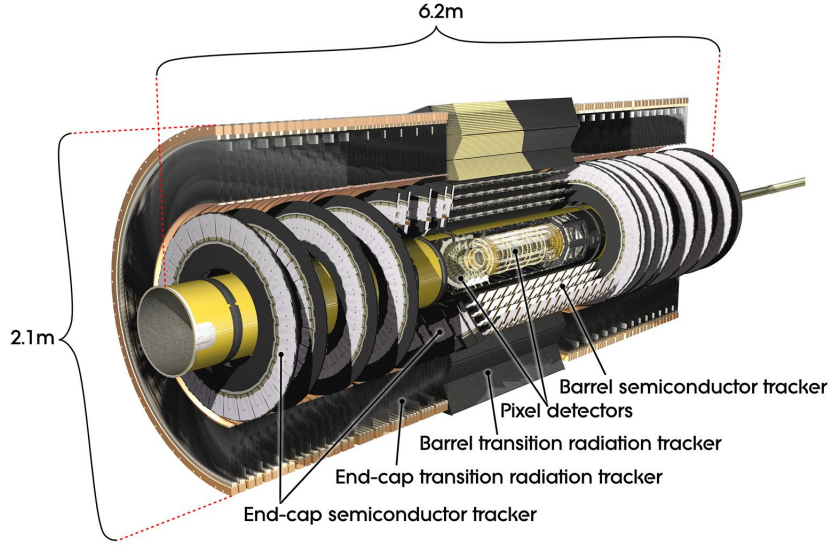


Figure 3.3: Layout of the ATLAS inner detector [37]

E denotes the particle energy and p_z the momentum component along the z -axis. This formula can be simplified by a high energy approximation where the mass is small compared to the momentum. The resulting variable is the *pseudorapidity*:

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

To describe the angular separation between two objects, the variable ΔR is used which is defined by

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

3.2.2 Inner Detector

The overall purpose of the inner ATLAS detector is the reconstruction of tracks of particles produced in the collisions, to measure their momentum and to detect secondary vertices. In Figure 3.3 the layout of the inner detector (ID) is shown. The inner part consists of high resolution semiconductor pixel strip detectors and the outer part of straw-tube tracking detectors. Both parts are embedded in a 2T solenoid field to bend charged particles and in order to measure their momenta.

Every 25 ns about 1000 particles emerge from the collision within the region $|\eta| < 2.5$. The result is a very large track density. Pixel and silicon micro-strip trackers (SCT) are precision tracking detectors and They are situated on concentric cylinders around the beam axis in the barrel region and on disks perpendicular to the beam axis in the end cap region. Overall they cover a region of $|\eta| < 2.5$. Around the collision point silicon pixel detectors are used to achieve a high granularity. Additionally straw tubes with a diameter of 4 mm of a transition radiation tracker (TRT) ensure a tracking up to $|\eta| = 2.0$. The TRT measures only track information in the R - ϕ plane and has a lower precision than the pixels and SCT. Nevertheless

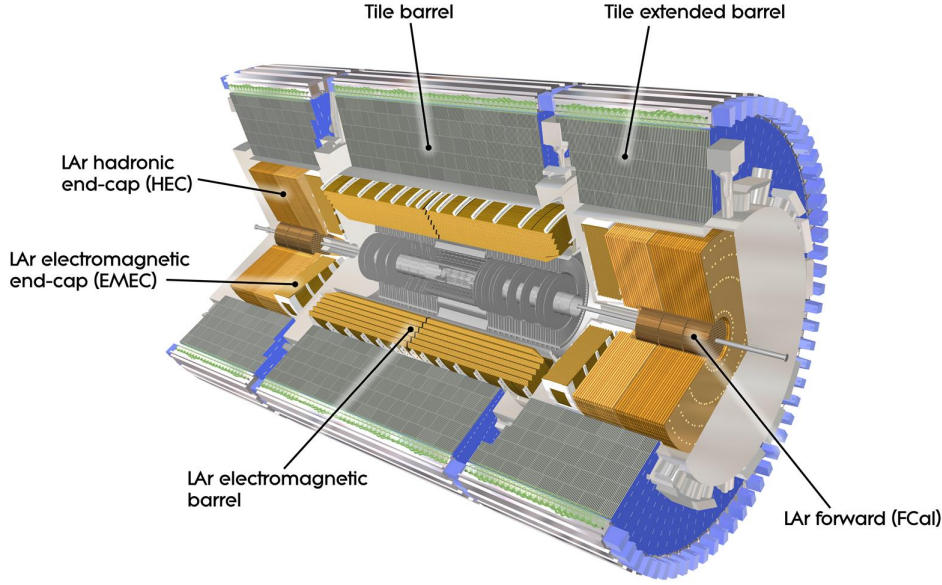


Figure 3.4: Schematic view of the ATLAS calorimeter system [37]

this is compensated by the large number of measurements and long measured track lengths. The gas mixture in the straw tubes is xenon based which allows to generate and detect transition radiation photons. This enhances the electron identification capabilities. With the combination of precision trackers at small radii and the TRT at larger radii a very good recognition pattern and a high precision in R , ϕ and z is achieved.

3.2.3 Calorimeter System

The ATLAS calorimeter system is shown in Figure 3.4. It covers the range $|\eta| < 4.9$. The individual calorimeters use different techniques adapted to the physics processes of interest and to the radiation environment over the large η -range. The η -region of the electromagnetic (EM) calorimeter is matched to the inner detector and shows a fine granularity. Hence, it is very well suited to measure electron and photon signatures with high precision. The rest of the calorimeters aim to contribute to the jet reconstruction and E_T^{miss} measurements for which a coarser granularity is sufficient.

The containment of the calorimeters plays an important role in limiting the energy deposition of electrons or jets in the muon system (punch-through). This can lead to serious damages in the muon chambers. Therefore, the calorimeter depth is an important parameter in the detector design.

²The terms jet and E_T^{miss} will be explained in Chapter 4

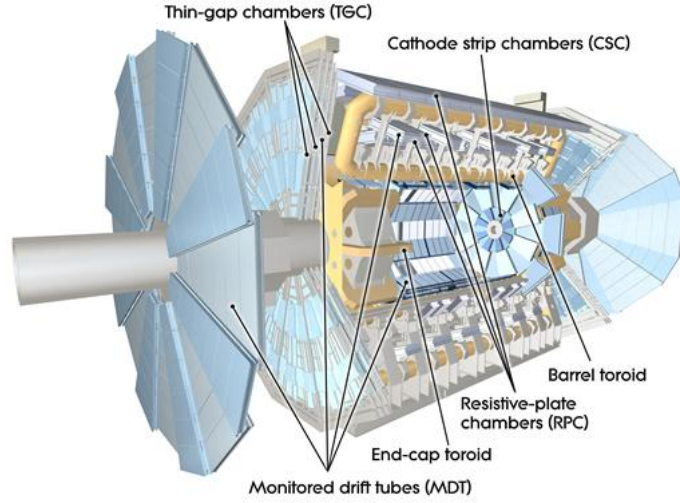


Figure 3.5: Schematic view of the ATLAS muon spectrometer [37]

Liquid Argon Electromagnetic Calorimeter

The EM calorimeter is constructed of lead and liquid argon (LAr) which has an excellent performance in terms of energy and position resolution. The calorimeter electrodes consist of kapton and the lead absorber plates are accordion-shaped which provides complete ϕ symmetry without azimuthal cracks. The EM calorimeter consists of a barrel part ($|\eta| < 1.475$) and two end-cap components ($1.375 < |\eta| < 3.2$). To correct for the energy lost by electrons and photons in the ID material, a pre-sampler detector is installed in the region $|\eta| < 1.8$. It consists of an active LAr layer.

Hadronic Calorimeter System

The hadronic calorimeter system consists of a tile calorimeter, a LAr hadronic end-cap calorimeter and a LAr forward calorimeter (FCal).

The tile calorimeter adjoins directly the EM calorimeter on the outside. It is a sampling calorimeter which uses steel as absorber and scintillating tiles as active material. It covers the region $|\eta| < 1.7$.

The hadronic end-cap calorimeter is placed directly behind the end-cap EM calorimeter with a pseudorapidity range of $|\eta| > 1.5$. It is a liquid argon detector like the FCal.

The FCal provides energy measurements up to $|\eta| = 4.9$ and is separated into three modules. The first one is made of copper and is optimized to measure electromagnetic processes. The other two modules are made of tungsten and have the primary aim to measure hadronic interactions.

3.2.4 Muon System

Muons are detected primarily in the muon spectrometer (MS) which is the very outer part of the ATLAS detector and contributes significantly to detector size. A schematic view of the MS is shown in Figure 3.5. Muons with transverse momenta in the range $3 < p_T < 200$ GeV

are not able to induce showers in the electromagnetic or hadronic calorimeters. They penetrate the detector without interacting due to their long lifetime of $\tau_\mu = 2.2 \mu\text{s}$ and their high mass of $M_\mu = 105.6 \text{ MeV}$ [6]. Hence, the loss of energy due to bremsstrahlung is small.

Due to these special muon properties and the importance of muons in physics processes a dedicated detection system that provides precise tracking, momentum and trigger information is required.

The MS covers the pseudorapidity range of $|\eta| < 2.7$. It consists of 4 main detector types: the monitored drift tubes (MDT) that measure tracks in most of the barrel pseudorapidity range, the cathode strip chambers (CSC) which do the tracking in the high pseudorapidity region, and the resistive plate and thin gap chambers, RPC and TGC, that are responsible for triggering in the barrel and the end cap region respectively. The RPC and TGC have an intrinsic high time resolution which is crucial for any efficient trigger.

The MS is located inside a toroidal magnetic field with a strength of 0.5 T in the barrel and 1.0 T in the end-cap region. In the transition region between the barrel and the end-caps ($1.4 < |\eta| < 1.6$) charged particles are bend by the combination of both fields.

For the momentum measurement, an accuracy of at least 10% up to momenta of $p_T \approx 1 \text{ TeV}$ is aimed. For that, a perfect knowledge of the magnetic field and of the alignment of the chambers up to a precision of $30 \mu\text{m}$ is crucial. 12000 optical precision sensors are installed in order to monitor deviations from straight lines of the spectrometer components and 1800 HALL sensors provide information about the magnetic field. The response from these sensors are used for momentum and track corrections.

3.2.5 Forward Detectors

In the very forward region of the ATLAS detector, close to the beam pipe, three smaller detectors are installed. Two of them are constructed to measure the luminosity delivered to the detector and one is designed to measure forward neutrons in heavy ion collisions.

The LUCID (Luminosity measurement using Čerenkov Integrating Detector) is located at $\pm 17 \text{ m}$ from the interaction point. It is the main online relative luminosity monitor using the principle of a Čerenkov luminosity counter. Consisting of 20 aluminum tubes, it detects inelastic p-p-scattering in the forward direction. The aluminum tubes surround the beam pipe directly and hence, have to be very resistant against radiation.

The ALFA (Absolute Luminosity for ATLAS) is the second forward detector measuring the luminosity. It is situated at $\pm 240 \text{ m}$ from the interaction point. This far away position allows to measure protons at scattering angles of $3 \mu\text{rad}$.

ALFA uses scintillation fiber trackers inside Roman pots³. This setup allows to measure up to 1 mm close to the beam.

The elastic scattering amplitude in forward direction is connected to the total cross section by the optical theorem. Hence, the measured amplitude can be transformed into the luminosity.

³Roman pots are cylindrical detector volumes attached directly to the beam pipe and separated from the vacuum only by a thin window.

The ZDC (Zero-Degree Calorimeter) is constructed to detect forward neutrons with $|\eta| < 8.2$ in heavy-ion collisions. It aims to measure the centrality of such collisions using its strong correlation to the number of very forward (spectator) neutrons.

The ZDC is located at ± 140 m from the collision point right where the straight beam pipe divides back into two separated beam pipes. It is made of tungsten plates perpendicular to the beam and quartz rods that penetrate the plates parallel to the beam axis.

3.2.6 Trigger and Data Acquisition System

The proton proton interaction rate at design luminosity amounts to 40 MHz. However, the event data recording is limited to 200 Hz by the available bandwidth of 300 MB/s which means that the number of initial events has to be decreased by a factor of 10^5 . The amount of recorded data is still about 3200 TB each year which is equivalent to the content of 7 km of CD-ROMs stacked on top of each other or 3 billion books.

To gain such a huge event rejection and to select the events of interest in ATLAS physics which have mainly cross sections many orders of magnitude smaller than the ones of QCD processes, a highly efficient trigger and data acquisition system (TDAQ) is necessary.

The ATLAS trigger system is a multiple level system that is highly configurable through combinations of different requirements and algorithms. These are referred to as *trigger chains*.

Having multiple trigger levels means that each decision from the upper level is refined by applying additional criteria.

There are three trigger levels. The *first level trigger* (L1) is hardware based using information from the calorimeters and the MS with reduced granularity and selects events at a maximum rate of 75 kHz. It defines Regions of Interest (RoI) by looking for interesting signatures from electrons, photons, muons, jets, large missing transverse energy or total energy. These RoI contain the η and ϕ information of the detected objects and a threshold, e.g. on the energy or transverse momentum.

The two software based triggers, the *second level trigger* (L2) and the *Event Filter* (EF), are also referred to as *High Level Triggers* (HLT). The L2 uses the full granularity and precision information of the data inside the RoI and reduces the event rate to 3.5 kHz. The EF scans the events passing the L2 and uses offline analysis algorithms, the latest calibrations, alignment measurements and the current magnetic field map to make a decision.

To reduce the dead time of the triggers, a buffering system at all trigger levels is used. It stores the data while waiting for the decision. The trigger algorithms are permanently developed and improved and therefore change over the data taking period.

Chapter 4

Object Reconstruction in ATLAS

From the signatures in the detector physical objects such as electron and muon candidates can be identified and reconstructed. In this chapter, the reconstruction and identification procedures of the object candidates used within this analysis are introduced.

4.1 Triggers

The triggers whose recorded data streams are analyzed within this work are electron triggers and muon triggers. Electron triggers respond to events containing at least one electron candidate and muon triggers respond to events containing hits in the MS. The triggered events are written to a disk separately which is why one event can be contained in both, the electron stream and the muon stream. If this is the case, the event is removed in one of the streams. Both, the electron triggers and the muon triggers that have been used within this work, have a p_T threshold of 24 GeV but are fully efficient only to events with object candidates that have a p_T of at least 1 GeV higher than the threshold.

4.2 Primary Vertex

The primary vertex is the vertex in an event with the highest sum of p_T^2 of all emerging tracks. It is used in calculations of any vertex related variable like the impact parameters. The longitudinal impact parameter z_0 is a measure for the minimal distance of a track from the primary vertex along the z -axis. The transverse impact parameter d_0 measures the shortest distance between a track and the primary vertex in the transverse plane.

The primary vertex is required to have at least three associated tracks in this analysis.

4.3 Muons

Within the ATLAS collaboration a dedicated group, called Muon Combined Performance (MCP) group, exists that works on the optimization of the muon identification and reconstruction [40, 41].

Muons are tracked through the whole detector, since they deposit energy fractions in the

muon spectrometer (MS) as well as in the inner Detector (ID). The tracks in both detector parts are reconstructed independently. The MS tracks are extrapolated back to the interaction point of the collision and an ID track is associated. A muon identification algorithm is applied to decide if the ID and MS entries indicate the existence of a muon candidate.

There are several strategies to identify muon candidates. In the analyses described in this thesis only two are of interest. One strategy is to combine ID tracks with full MS tracks. This is called *combined reconstruction algorithm*. Another strategy is the extrapolation of ID tracks to the MS and combine them with segments reconstructed in MS stations. In this case there is no need for a complete track in the MS which is why this method is called *segment tagging algorithms*.

Once the muon candidates are identified, a muon collection is built. The muon momenta are calculated from the bending of the tracks in the magnetic field and are corrected for energy losses in the calorimeters.

4.4 Electrons

The Egamma working group within the ATLAS collaboration works on the optimization of the electron and photon identification and reconstruction [42, 43]. There are two reconstruction algorithms for electrons in the ATLAS detector.

The *cluster based algorithm* is mainly designed for high p_T electrons. As a seed it uses a cluster in the EM calorimeter to which a track in the ID is matched. The matching is done by an algorithm that compares the position in η and ϕ of the cluster with the corresponding positions of the tracks.

The second algorithm, the *track based algorithm*, was developed for electrons with low p_T and for electrons that result from quark decays and have no isolated tracks. The algorithm is seeded by tracks that fulfill special quality cuts. They are extrapolated to the EM calorimeter and a cluster is created around the track [44].

The electron four-vector is reconstructed from the energy measurement in the calorimeter. The energy in the associated cluster cells is summed up and the direction is derived from the associated track.

4.5 Jets

Jets are the result of confinement which is a feature of the strong force. Confinement is the phenomenon that color charged particles cannot be isolated and therefore have never been observed in unbound states. If a bound state (being color neutral) of color charged particles is split apart, the potential energy in the gap between the constituents increases with increasing distance such that new color charged particles can be produced. The result are again bound states with white color.

This production of new particles via the strong force (hadronisation) takes place in high energetic interactions of quarks with other particles or the detector material. Due to the avalanche effect and the feature that gluons couple to each other, a bunch of hadrons can be produced that is referred to as jet. The track of the initial hadron will be wrapped into a cone of new particles.

To each jet a property called *Jet Vertex Fraction* (JVF) is associated. The JVF of a jet i and a vertex a measures which fraction of the sum over all track p_T of the jet constituents results from the vertex a . If all tracks within a jet emerge from vertex a , the JVF is equal to one. However if there are tracks in the jet whose particles were produced in a vertex b , $0 < \text{JVF} < 1$ applies.

Jets are reconstructed from topological clusters in the hadronic and EM calorimeters. A so called *anti- k_T algorithm* is used [45] which calculates the distances between two calorimeter clusters i and j , and one cluster i and the beam pipe B by

$$d_{ij} = \min(k_{Ti}^{-2}, k_{Tj}^{-2}) \frac{\Delta_{ij}^2}{R^2} \quad (4.1)$$

$$d_{iB} = k_{Ti}^{-2}, \quad (4.2)$$

where $\Delta_{ij} = (Y_i - Y_j)^2 + (\phi_i - \phi_j)^2$, k_{Ti} denotes the jet transverse momentum, Y_i the rapidity and ϕ_i the azimuthal angle. R is the maximal cone size of the jet and is set to 0.4 throughout this work. Within an event, entries with high transverse momenta from hard particles and with small transverse momenta from soft particles occur. By definition, the distance d_{ij} between a hard particle and a soft particle is smaller than the distance between two similarly separated soft particles. In the clustering procedure, the distance d_{1j} of cluster 1 to all other entries j will be calculated and the cluster 1 will be combined with the cluster to which the distance is minimal. By definition of d_{ij} , the probability that soft particles cluster with hard ones is significantly higher than to cluster among themselves.

If there are two hard particles 1 and 2 in the event, three scenarios are possible:

- $2R < \Delta_{12}$: Each hard particle will accumulate all the soft particles within a circle of radius R around its cluster resulting in two conical jets.
- $R < \Delta_{12} < 2R$: Two hard jets will be reconstructed, accumulating soft particles within a circle of radius R . There will be an overlap region of the circles. The particles contained in that region will be accounted to the jet reconstructed from the hard particle with the higher k_T . If $k_{T1} = k_{T2}$ the overlap region will be divided into two equal parts.
- $\Delta_{12} < R$: The particles 1 and 2 will form a single jet. If $k_{T1} \gg k_{T2}$ applies, a conical jet around the particle 1 will be reconstructed. If, however, $k_{T1} \sim k_{T2}$, the shape of the jet will not be conical any more but will be the union of the cones of radius R around the hard particles combined with a cone of radius R centered around the final jet.

A special case of the jet identification is the identification of jets induced by b-quarks. B-tagging algorithms use the relatively long life time of B hadrons¹ of the order of 1.5 ps [6]. Therefore, the the primary and the vertex of the B decay are separated. This separation is quantified by the impact parameters of the tracks coming from the decay. Additionally the relatively large mass of the B hadrons of more than 5 GeV results in opening angles and transverse momenta of the decay products relative to the B hadron flight direction that are

¹ B hadrons are particles consisting of two or three quarks and/or anti-quarks, where at least one of them is bottom like.

different compared to other jets. This property is taken into account as well by the b-tagging algorithms [46].

The energies of reconstructed jets are measured at the electromagnetic energy scale which means that only the energy from charged particles in the jet is measured in the calorimeter. The portion of neutral particles is taken into account by a correction factor which is derived from simulations[47].

4.6 Missing Transverse Energy

The missing transverse energy $\vec{E}_T^{\text{miss}}$ is defined as the sum of the transverse momenta of all objects measured in the detector. Since the momentum of the proton partons is not well known before the collision due to QCD effects in the proton, the transverse momentum is the only known variable. The protons are accelerated only in the z direction along the beam pipe axis, hence the transversal component of the parton momenta is negligible and the sum of all transverse particle momenta is considered to be zero before the collision. If the transverse momenta after the collision do not add up to zero we can conclude that particles were generated that escaped without detection. Among the SM particles this is only possible for neutrinos. They have negligible energies which is why their momenta are equal to their energies. Hence, the absolute value E_T^{miss} is a measure for neutrino energies.

$\vec{E}_T^{\text{miss}}$ is calculated in a first step from the measurements in the electromagnetic and hadronic calorimeters and from reconstructed muons.

The $\vec{E}_T^{\text{miss}}$ contributed to muons is calculated from the transverse momentum of stand-alone muons in order to not double count the energy lost by muons in the calorimeters. However, in order to suppress fake muons reconstructed from hits induced by high energetic jets in the MS, only muons with a matched inner detector track are taken into account.

The $\vec{E}_T^{\text{miss}}$ contributed to the calorimeters is calculated as the sum of the transverse energy of the topological clusters taking into account their position and hence, the direction of $\vec{E}_T^{\text{miss}}$. The electromagnetic calorimeter has a geometrical acceptance of $|\eta| < 3.2$ and the hadronic calorimeter of $|\eta| < 4.9$ (see Section 3.2.3). This wide coverage of the transverse region allows to measure nearly all transverse momenta in an event in clusters.

In a second step, the $\vec{E}_T^{\text{miss}}$ measurement is refined by associating to each cluster a high p_T object from which the cluster was induced. The initial value of $\vec{E}_T^{\text{miss}}$ is then replaced by the sum of the object transverse momenta plus the energy in clusters that could not be matched to a reconstructed object [48].

4.7 Resolving Ambiguities

After the object reconstruction, physical objects that have been reconstructed as two separated objects in the detector have to be removed. In this work, three types of ambiguities have to be resolved:

- Between electrons and jets: As described in the Sections 4.4 and 4.5, EM calorimeter entries are used to reconstruct electron candidates and jet candidates. Therefore, an

electron candidate is always reconstructed as a jet candidate as well. If the jet candidate lies inside a cone of radius $R = 0.3$ around an electron candidate the jet is deleted.

- Between muons and jets: The calorimeter isolation of muons reduces the probability that the muon emerged from a hadron decay. However, if a jet candidate still lies within $R = 0.3$ to a well isolated muon candidate, the event is discarded since the reason for this occurrence is not well understood. It could result from in-flight-decays of B mesons.
- Between muons and electrons: High energetic muons can radiate photons that may convert to electrons and positrons by pair production. These produced leptons are not of interest since they are not related to the processes in the proton-proton collision. Hence, every electron that is found within $R = 0.1$ to a muon is rejected.

4.8 Pile-Up

Pile-up refers to the case that several collisions take place with such a small time separation that they are recorded in one event. In general, only one of these interactions is responsible for releasing the trigger. There are two types of pile-up:

- In-time pile-up: More than one collision takes place in one bunch crossing.
- Out-of-time pile-up: Due to the integration time of the detector components the sub-detectors are also sensitive to tracks from bunch crossings before or after the main interaction and hence, result from other events. The sensitivity of the sub-detectors on such tracks depends on the detector type and the distance to the collision point. For example, the LAr calorimeter is sensitive to 38 bunch crossings with a bunch spacing of 25 ns.

Chapter 5

Monte Carlo Event Generation

For claiming discoveries of new physics, it is essential to compare measured data to theory predictions. When having elaborated a theory, pseudo data sets can be produced which reflect the detector output under the assumption that the theory is true. These data sets are also suited to be used in order to determine the detector performance by comparing measured well known Standard Model processes to their expectations in full detector simulations. In the event generation procedure Monte Carlo (MC) techniques are widely used which is why simulated samples¹ are also referred to as MC samples [49].

5.1 Event Generation Procedure

In the following, the steps for the generation of simulated events are outlined.

Matrix Element Integration: In the first step, the matrix element of the process of interest is integrated numerically over the phase space. For this calculation, most generators use the MC method.

Event Generation: The second step is the event generation within the phase space. It produces a list of outgoing particles with their properties charge, spin and Lorentz-vector according to the kinematics of the process of interest. Here, the Monte Carlo technique is applied again.

In a hadron collider like the LHC, the interactions of primary particles take place at parton level. Hence, the parton density functions (PDF) are applied to describe the kinematics of initial state particles. They are measured experimentally and cannot be calculated perturbatively. However, the hard interaction (the interaction with the largest momentum transfer) can be evaluated in perturbation theory to a fixed order of the coupling constants.

According to the factorization theorem, the total interaction can be factorized in a part that is evaluated from experimental observations, i.e. the PDF, and one part calculated perturbatively. The transition between the two regions takes place at an energy scale called *factorization scale* μ_F and has to be chosen by hand. There is no rule, which μ_F is the right one, there are only more or less suited energy scales. Well suited are factorization scales that take into

¹The term sample refers to a collection of simulated events for one distinct process and set of parameters.

account the kinematics of the process of interest, for example $\mu_F = 2M_W$ if two W bosons are exchanged.

Parton Shower: The parton shower takes as input the list of outgoing particles from the simulated process and models decays of short living resonances, corrections due to Bremsstrahlung in the initial and final state, interactions of other partons at lower energy scales, also referred to as *underlying event*, beam remnants and the hadronization of the partons due to the strong force.

The state of the simulation after the shower is denoted as *truth level* since no detector effects are involved yet.

Detector Simulation: Interactions of generated particles with the detector materials are simulated in the second step by the program GEANT4 [50, 51] with high precision. In order to model the detector response as close to reality as possible, the detector geometry and the material properties have to be known very well. In addition pile-up has to be included since mis-measurements can occur due to this effect. It is simulated by superimposing events with low energetic processes with the event containing the high energetic process of interest. Here, a so called *MU distribution* is applied which is a discrete distribution of the average number of collisions per bunch crossing. Since the beam conditions change during data taking, the simulated pile-up has to be adapted to the analyzed data.

The detector simulation is the most time intensive step in the event generation chain.

Digitalization: In the digitalization step, the output from the readout electronics is produced. It contains the detector response of the merged pile-up and signal events. This output is equivalent to the one produced during the real measurement.

Object Reconstruction: The last step is the same for data and simulation. A reconstruction algorithm is applied to the digitized detector signals. It creates analysis-oriented data structures by forming clusters from the energy deposits in the calorimeter and associating the hits in the tracking detectors to tracks. From these structures the physics objects that are used in the analyses are formed.

The state of the outgoing events is referred to as *reconstruction (reco) level*.

In order to increase the statistics of the MC samples, more events than the recorded luminosity would provide, are generated. Additionally, certain phase spaces are enriched by cutting on kinematic variables in the event generation step. This introduces a generator filter efficiency ϵ_F which is connected to the integrated luminosity of the simulated events $\int L_{MC} dt$ by

$$\int L_{MC} dt = \frac{N_{MC}}{\sigma \cdot \epsilon_F}, \quad (5.1)$$

with N_{MC} being the number of MC events and σ the cross section in the full phase space without any kinematic requirements. In general, the product $\sigma \cdot \epsilon_F$ is calculated in the matrix element integration step.

In order to scale L_{MC} to the integrated luminosity of the real data, a scaling factor ω is applied to the generated events:

$$\omega = \frac{L}{L_{\text{MC}}} = \frac{L \cdot \sigma \cdot \varepsilon}{N_{\text{MC}}}. \quad (5.2)$$

5.2 Corrections to Simulated Events

Event though the geometry and material properties of the ATLAS detector are well known, the description of nature by the detector simulation, is still an approximate model. For practical reasons it is limited in detail and accuracy. Therefore, corrections are applied to the simulated events in order to match the observed data. Additionally, some details of the experimental setup like the amount of pile-up or detector defects change over the data taking period and have to be taken into account by corrections as well.

In detail, the following corrections are applied to the simulated samples used within this work:

- **Pile-up Corrections:** Pile-up properties are in general not known at the time of the production of simulated events since the beam conditions change during the run period. Hence, simulated pile-up is in bad agreement with the observation. To rectify the disagreement, the simulated events are reweighed.
- **Trigger Efficiency Corrections:** The trigger efficiencies of the used triggers in the analysis are measured in data and in simulated samples. In the case of electron triggers the SM processes $Z \rightarrow ee$ and $W \rightarrow ve$ [42] and in the case of muon triggers the SM process $Z \rightarrow \mu\mu$ [40, 41] are studied and correction factors are derived.
- **Jet Energy Correction:** The jet energy is measured at the electromagnetic scale and corrected back to the hadronic scale where neutral particles are taken into account as well. The correction factors have a dependence on E_T and η . Additionally a correction on the jet energy resolution is applied to simulated events [47, 52].
- **Lepton Efficiency Corrections:** Correction factors to account for the discrepancy between the simulation and the observation in reconstruction, identification, isolation and impact parameter efficiency of electrons and muons are applied. For electrons, they are determined from $W \rightarrow ve$, $Z \rightarrow ee$ and $J/\Psi \rightarrow ee$ measurements and depend on η and E_T . For muons, they are obtained by studying the SM process $Z \rightarrow \mu\mu$ and depend on p_T , η and the azimuthal angle ϕ . These processes are chosen since they produce well isolated leptons with clear signatures and well known kinematics.
- **Lepton Energy Corrections:** The simulated energy and momentum resolution of the peak in the invariant muon mass spectrum of the SM process $Z \rightarrow \mu\mu$ is compared to data. From this, a momentum scale factor and a smearing factor to correct for the resolution is derived [53]. Corresponding factors are evaluated for electrons by analyzing the SM process $Z \rightarrow ee$.

- $\vec{E}_T^{\text{miss}}$ **Corrections:** The corrections on the lepton and jet energies and momenta influence the expected missing transverse energy. Hence, these corrections are propagated back to $\vec{E}_T^{\text{miss}}$ by

$$\vec{p}_{T,e} + \vec{p}_{T,\mu} + \vec{p}_{T,\text{jet}} + \vec{E}_T^{\text{miss}} = \vec{p}'_{T,e} + \vec{p}'_{T,\mu} + \vec{p}'_{T,\text{jet}} + \vec{E}_T'^{\text{miss}} \quad (5.3)$$

where the primed variables are the corrected quantities.

Within the ATLAS collaboration dedicated groups exist that provide sets of these correction factors depending on the reconstruction and trigger algorithms used in the analysis.

5.3 The Event Generator WHIZARD

The event generator WHIZARD [54, 55] is designed to calculate tree-level matrix elements in LO perturbation theory. It includes e.g all SM processes and is also able to simulate processes from the Minimal Supersymmetric SM and anomalous coupling processes. Particularly, anomalous quartic gauge couplings are implemented with the electroweak chiral Lagrangian approach described in Section 2.3.1. The electroweak symmetry breaking is induced by a non-linear realization of the Σ field. To unitarize this effective theory, the K-Matrix unitarization method explained in Section 2.4 is implemented.

Using the interface O'MEGA, the matrix element for every possible process within a given model is computed. The beam structure has an influence on the kinematics as well and is taken into account using PDF.

All tree-level matrix elements for a given initial and final state are computed in the first step. This implies that all subprocesses are included in the final output. Individual subprocesses like QCD processes or anomalous couplings can be switched off in setting the respective coupling constants to zero.

In the list of final states quarks and τ leptons are present. These have to be hadronized and decayed respectively by parton shower generators like PYTHIA [56].

After the showering, the detector simulation is executed.

Chapter 6

Vector Boson Scattering

Vector Boson Scattering (VBS) is defined as the interaction of two vector (gauge) bosons resulting in two vector bosons in the final state and is a purely electroweak process. The scattering process allows three and four boson vertices and depending whether the final vector bosons decay hadronically or leptonically various channels are possible. Figure 6.1 shows an illustration of the VBS process. The black circle can be replaced by an interaction process between the two vector bosons.

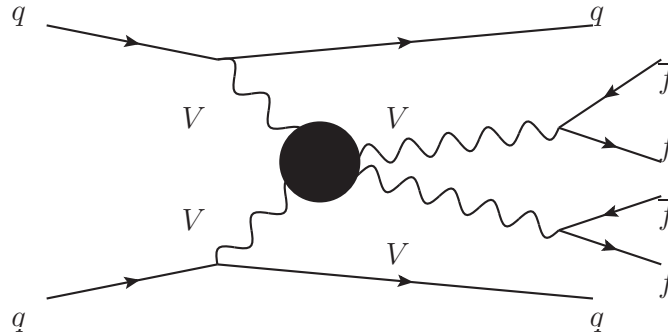


Figure 6.1: Scheme of the scattering of two vector bosons indicated with V . f stands for fermions, q for quarks and the black circle for all possible interactions of the two vector bosons.

6.1 Motivation of Observing Vector Boson Scattering

Since VBS is a purely electroweak mediated process, it is sensitive to the EWSB mechanism and to physics beyond the SM. If there was no light SM Higgs boson, the scattering process of longitudinally polarized vector bosons is expected to become strong and to violate unitarity above an energy of $\sqrt{\hat{s}} = 1.2$ TeV [57], where $\sqrt{\hat{s}}$ is the center of mass energy of the two initial vector bosons. The propagator of a massive spin-1 field contains a term that does not decrease with increasing momentum, resulting in unphysical cross sections at high energies. The contribution of the Higgs boson or any other effect resulting from EWSB cancels out these terms.

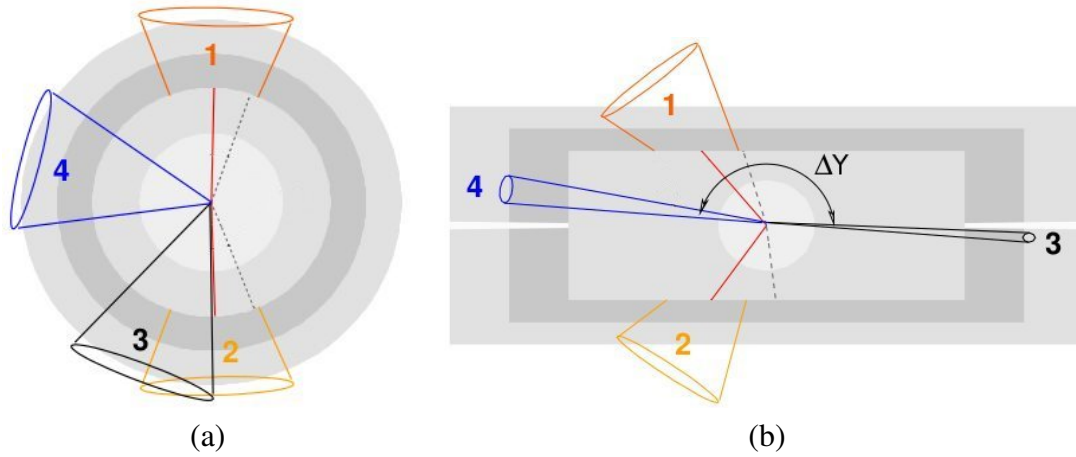


Figure 6.2: Schematic view of the VBS WW topology in the x - y -plane (a) and the y - z -plane (b). The cones marked with 1 and 2 are the two central leptons and 3 and 4 are the tagging jets. (Edited graphic from [58])

Recently, a scalar boson resembling the SM Higgs boson was discovered. It is a hint on the realization of the EWSB by a Higgs field. Still, VBS could differ from SM predictions. Some Theories consider the Higgs boson as a composite particle which would indicate that additional resonances contribute to the EWSB. At high energies, other mechanisms than the ones contained in the SM can apply as well.

Whether the Higgs mechanism unitarizes VBS processes fully or only partially can be seen in the energy dependence of VBS above energies of the order of the Higgs mass.

6.2 Topology

All VBS processes are characterized by two high energetic jets referred to as *tagging jets*. They are produced by the two quarks that radiated the vector bosons. The tagging jets are expected to be well separated in rapidity Y and have large transverse momenta. Therefore, background from QCD processes can be well rejected since they show in general more centrally distributed jets and more jets overall. In VBS processes central jets, also referred to as *mini-jets*, are rare due to the lack of exchanges of gluons between the initial quarks. Final states, from leptonically decaying vector bosons have lower branching ratios than the ones from the hadronic decay channels. However, channels without leptons are very difficult to distinguish from background processes in a hadron collider like the LHC due to a large number of QCD processes resulting in multijet final states. Channels like $qq \rightarrow WW \rightarrow l\nu l\nu$ or $qq \rightarrow WZ \rightarrow l\nu ll$ have clean signatures because of the excellent lepton reconstruction capabilities of the ATLAS detector. Therefore, the focus lies on leptonic final states in this work. Figure 6.2 shows a typical VBS topology of WW scattering in the x - y - and the y - z -plane.

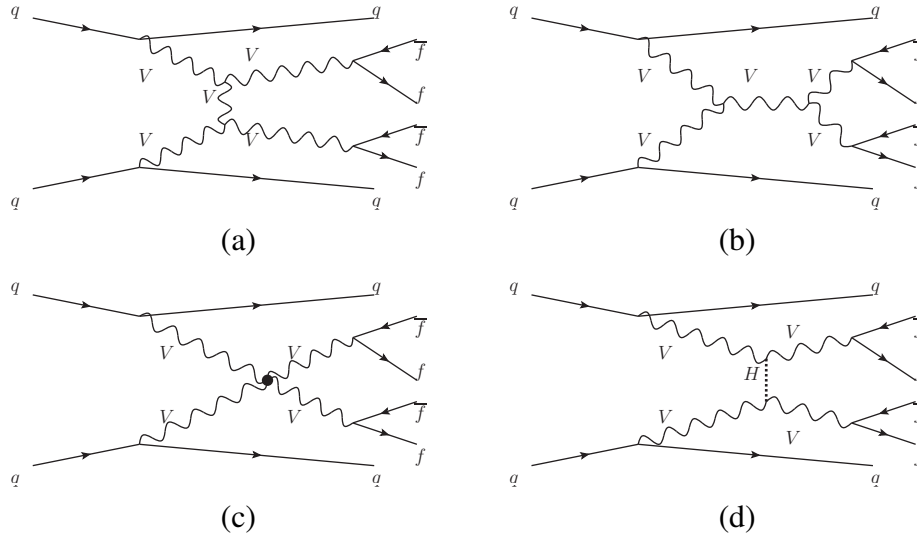


Figure 6.3: Examples for Feynman diagrams of VBS processes. Vector bosons are denoted with V , fermions with f and quarks with q .

6.3 Classification of Vector Boson Scattering Processes

VVjj denotes the production of two vector bosons and two jets. This is the case in VBS but also in other processes.

The black circle in Figure 6.1 can be replaced by the Feynman diagrams shown in Figure 6.3 which are an exemplary selection. The diagrams (a), (c), and (d) contribute to the scattering of two equally charged W bosons which will be investigated in Chapter 7. Among the non-VBS VVjj processes, some diagrams are gauge invariantly separable¹ from VBS diagrams (e.g. all VVjj QCD processes) and some are not. The latter belong to VVjj EW processes together with the VBS processes.

VVjj EW denotes only electroweak processes which are of the order six in the expansion in the weak coupling constant α_{EW} ($\mathcal{O}(\alpha_{EW}^6)$). Beside VBS, these are for example the production of 3 vector bosons from which one decays hadronically, the electroweak radiation of two vector bosons and the production of a vector boson and a Higgs boson decaying to two vector bosons. They contribute to the background in the search of VBS, but since they can be separated gauge invariantly from the signal process, they can be suppressed by appropriate kinematic cuts in the event selection. Figure 6.4(c) shows an example for non-VBS processes that are gauge invariantly separable from the signal. It can be suppressed by a cut on the invariant jet mass M_{jj} .

Processes that are not gauge invariantly separable from VBS processes are not of interest but are included in the signal. In Figure 6.4(a) and (b), processes that cannot be separated gauge invariantly from VBS are shown.

¹Gauge invariantly separable are all diagrams that can be gauged independently without violating gauge invariance. Processes that are not gauge invariantly separable have to be summed up before the gauge.

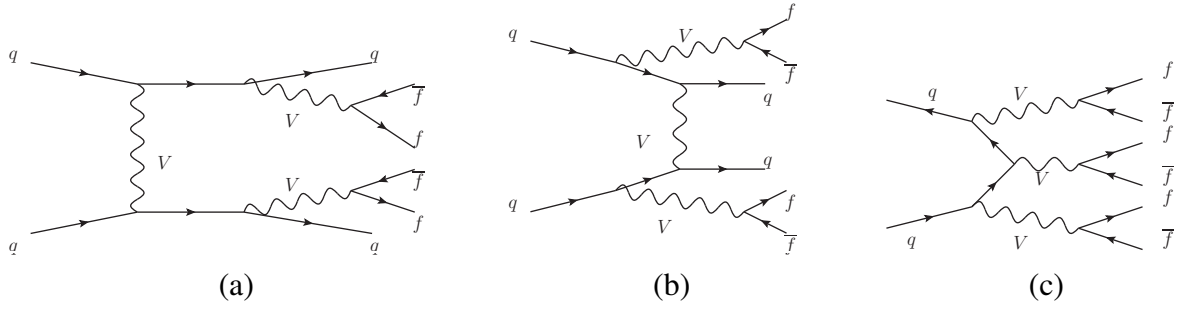


Figure 6.4: Feynman diagrams of VVjj EW processes where no VBS takes place. Diagrams (a) and (b) are examples for processes not being gauge invariantly separable from the VBS signal and (c) is an example for a process that can be separated and therefore suppressed by selection criteria.

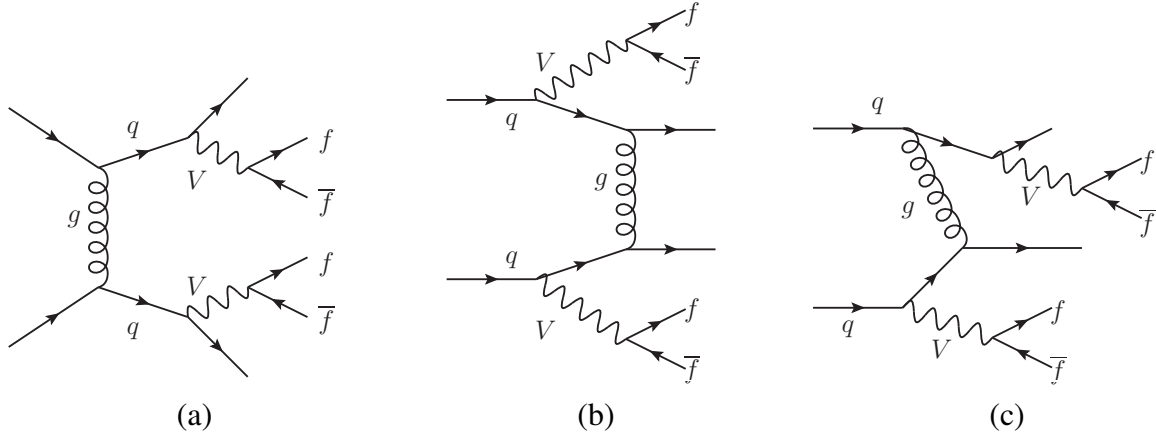


Figure 6.5: Examples for Feynman diagrams of VVjj QCD processes.

VVjj QCD includes all diagrams that are of order 4 in electroweak interactions and of order 2 in strong interactions with the strong coupling α_s ($\mathcal{O}(\alpha_{EW}^4 \alpha_s^2)$). Figure 6.5 shows three examples for VVjj QCD processes in $W^\pm W^\pm$ production. They can be suppressed by kinematic cuts in the event selection.

Between VVjj EW and VVjj QCD, interference can occur. It is considered to be constructive and therefore increases the cross section of VBS processes.

Chapter 7

Measurement of aQGC in $W^\pm W^\pm$ Scattering

7.1 The $W^\pm W^\pm jj$ Process

The production of same sign W boson pairs in the SM and their scattering is going to be observed for the first time from the WW same sign analysis group in ATLAS. The focus lies on the electroweak production via vector boson scattering and the decay to electrons or muons and neutrinos. This process will be referred to as $W^\pm W^\pm jj$ in the following.

The description of the cross section measurement in this section follows the structure of the note [59] which is a publication in preparation and therefore, restricted to ATLAS members. The systematic uncertainties are consistent with the note, however, the results of the cross section and the aQGC measurement differ about 10% from the results in the publication because of some simplifying assumptions. For example, the b-tagging scale factor was not taken into account.

The advantage of studying the scattering of same sign W bosons instead of opposite signed ones ($W^\pm W^\mp$) is the significantly lower QCD contribution. Same sign W bosons cannot be produced from gluon-gluon initial state processes in LO. Otherwise charge conservation would be violated. QCD and EW processes therefore have almost the same cross section. For opposite sign W bosons, the additional QCD diagrams increase the QCD process cross section by a factor of about 30. In Table 7.1, the production cross sections for $W^\pm W^\pm$ and $W^\pm W^\mp$ scattering are shown, separated into the QCD and EW contributions. The values were calculated by the event generator SHERPA [60, 61, 62].

The interference between $W^\pm W^\pm jj$ EW and $W^\pm W^\pm jj$ QCD is estimated to contribute with 6-10% to the total cross section depending on the selected phase space. However, it is not taken into account in this analysis since these numbers were not yet known when most of the results in this work had been produced. For the aQGC measurement which will be described in Section 7.6, this means that derived the aQGC parameter constraints are conservative¹ as the consideration of the constructive interference leads to tighter constraints.

¹The term conservative in the context of limit setting implies that the confidence interval covers more than the desired portion. Hence, the constraints are looser than they ought be.

Process	VVjj EW	VVjj QCD
$W^\pm W^\pm$	19.5 fb	18.8 fb
$W^\pm W^\mp$	91.3 fb	3030 fb

Table 7.1: EW and QCD production cross sections of $W^\pm W^\pm$ and $W^\pm W^\mp$ at $\sqrt{s} = 8$ TeV. The values were calculated by the event generator SHERPA in the phase space: $M_{ll} > 4$ GeV, $p_T^l > 10$ GeV, $p_T^l > 5$ GeV.

7.1.1 Topology

The focus in this analysis lies on the leptonic final states. $W^\pm W^\pm jj$ results in two final state charged leptons (electrons, muons or their antiparticles) with equal charge, two jets and two neutrinos. Tau decays are excluded from the analysis. In the following, the term “lepton” will include only electrons and muons.

The final state is divided into three channels depending on the final state leptons:

- two electrons or positrons (ee-channel)
- two muons or anti-muons (mm-channel)
- one electron and one muons or one positron and one anti-muon (em-channel)

In the following, when speaking of electrons e and muons μ , their antiparticles are implied as well. The specific properties of the final state particles result in a very good background suppression:

- The neutrinos result in missing transverse energy E_T^{miss} .
- The signature of two equally charged leptons in $W^\pm W^\pm$ scattering excludes the SM backgrounds $W^\pm W^\mp$, $t\bar{t}$ and Z+jets if the lepton charges are reconstructed correctly.
- As described in Chapter 6, a characteristic property of VBS is the presence of two forward jets (tagging jets) in opposite hemispheres. They carry large transverse momenta, have a large invariant mass M_{jj} and are well separated in rapidity which is expressed in the variable ΔY_{jj} . The tagging jets are defined as the two jets with the highest transverse momenta in the event. SM backgrounds and $W^\pm W^\pm jj$ QCD processes can well be reduced by selection criteria on ΔY_{jj} and M_{jj} , since in these processes more tagging jets lie in the central region of the detector and are less energetic.

This makes $W^\pm W^\pm jj$ an ideal process to be analyzed because and a good signal to background ratio is expected.

Figure 7.1 shows the the projection in the x - y - and the y - z -plane of a measured event in the em-channel with $W^\pm W^\pm jj$ topology. The forward jets are well separated in rapidity and are high energetic with energies of 230.3 GeV and 430.4 GeV, the muon has a transverse momentum of 29.55 GeV and the electron of 46.2 GeV. The missing transverse energy amounts to 54.5 GeV.

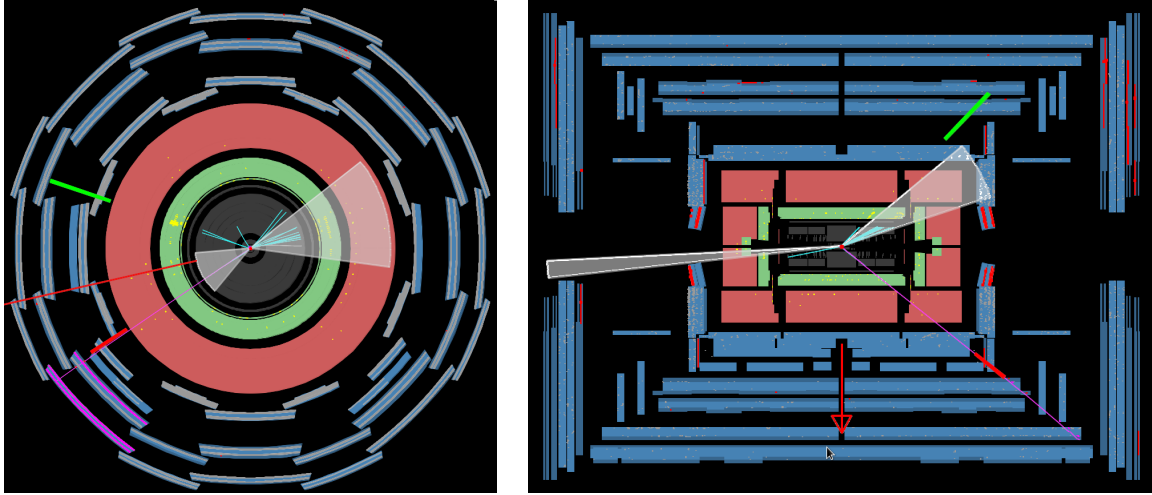


Figure 7.1: Display of an observed event in the em-channel with $W^\pm W^\pm jj$ topology (Run-number: 214544, Eventnumber: 170249513). On the left, a cut in the x-y-plane and on the right a cut in the y-z-plane is shown. The jets are marked by white cones, the electron direction by a green line in the MS, the muon track by a purple line, and the direction of E_T^{miss} by a red arrow.

7.1.2 Background Processes

The $W^\pm W^\pm jj$ signature can be mimicked by SM processes when taking into account that mis-identifications and mis-measurements are possible.

The following sources contribute to the total background:

- **$W^\pm W^\pm jj$ QCD** was already mentioned in Section 7.1. It is a background which has a cross section of the same order as $W^\pm W^\pm jj$ EW and can be well suppressed by selecting events with large ΔY_{jj} .
- **WZ +jets and ZZ +jets** denote the background due to diboson production of a W and a Z boson or two Z bosons respectively, in association with jets. These processes contribute when the bosons decay leptonically and only two same sign leptons pass the event selection or are reconstructed at all. By coincidence two of the jets can have high transverse momenta and a forward topology. The high E_T^{miss} might result from heavy quark decays or the unsuccessful reconstruction of leptons. In this background WZ/ZZ VBS processes are included as well. WZ +jets is one of the dominant backgrounds in the $W^\pm W^\pm$ analysis and around one third of the total WZ background in the signal region results from EW processes.
- Processes where a lepton is faked by a jet will be denoted as **fake background**. Processes that contribute are the production of a W boson in association with jets (W +jets), the production of a top- and an anti-top-quark ($t\bar{t}$), the production of a single top-quark (single top), and QCD multijet processes. They have signatures of two equally charged leptons if one or two jets are mis-reconstructed or a hadron decay takes place that produced a real lepton that passes the object selection. Since jet-faked leptons are in general not well isolated and often emerge from b-quark decays, this background can

be suppressed by tight isolation criteria. A cut on E_T^{miss} energy helps as well, since it is in general small for QCD multijet processes due to the lack of neutrinos.

- **$W\gamma$ +jets** denotes background due to the production of one W boson in association with one photon and jets. It has the same signature as the signal if the photon is reconstructed as an electron usually through asymmetric conversion into an electron-positron-pair (e^+e^-).
- The **charge mis-identification (charge misID) background** includes processes where two oppositely charged leptons are recognized as equally charged leptons. This background originates mainly from $t\bar{t}$, the production of two oppositely charged W bosons in association with jets ($W^\pm W^\mp$ +jets) and the production of a Z boson or a virtual photon in association with jets (Z/γ^* +jets). The misID rate for muons is negligibly small. Therefore, only the charge misID of electrons is studied. A Z veto in the ee channel is applied in order to suppress the dominant contribution from $Z \rightarrow ee$. Since top quarks decay with a branching ratio of 99.8% to a b quark and a W boson², the $t\bar{t}$ background can be suppressed very efficiently by a b -jet veto.
- **$T\bar{T}$ +V** is a background where a top and an anti-top quark are produced in association with a vector boson. It mimics the signal signature if one lepton from the top quark decays is reconstructed and has the same electric charge as the lepton resulting from the vector boson decay. The jet signature can be realized by the jets coming from the two quarks.
This background is suppressed by a b -jet-veto and isolation requirements of the leptons.
- **Double parton scattering (DPS)** denotes processes where two highly energetic interactions between two partons from each proton take place. Processes that can occur in DPS and give the same signature as $W^\pm W^\pm$ VBS are for example $W^\pm$ +jets & $W^\pm$ +jets, W +jets & Z +jets, WW & dijets, and WZ & dijets.
This background was found to be negligibly small and is therefore omitted in the following.

A good knowledge of all background contributions is crucial for any measurement. To estimate the contributions from faked leptons and leptons with mis-reconstructed charge, methods that measure a fake and a charge misID factor in data were used. They will be described briefly in the following two subsections. The other background contributions were estimated from MC simulations and compared to data in control regions in order to validate that the simulation models well the physics processes and the detector response. The MC samples can be found in the Appendix C.1. Backgrounds from events where a muon is mis-reconstructed as an electron, e.g. due to final state photon radiation, were proven to be negligible after MC studies [59].

²This branching ratio is predicted by the SM.

Estimation of Charge MisID Background

The charge misID rate for electrons and muons in $\sqrt{s} = 8$ TeV ATLAS data was studied in [63]. For muons this rate was found to be immeasurably small. Hence, it is neglected and only the charge misID factor for electrons is evaluated.

The main sources of mis-identification of electron charges is Bremsstrahlung. It can be emitted by the electron when it passes through material. The photon may convert into an electron-pair. If it decays asymmetrically, only one electron may be reconstructed. With a probability of 50% it has the same charge as the other lepton in the event. The electron p_T is then biased to lower values since a part of the photon momentum is carried away by the other electron. Other minor sources are the wrong curvature at high electron p_T or the wrong track association to the cluster.

The charge misID rate of electrons is estimated using two different methods in order to cross check the results. These are a Likelihood method and a tag-and-probe method. In both cases $Z/\gamma^* \rightarrow ee$ events are selected from data where the electrons pass the same selection criteria as applied in the analysis object selection. Those criteria will be introduced in Section 7.2.1. The selected events are then divided into same sign (SS) and opposite sign (OS) events depending on the electron charges. Most of the events are Z boson decays. The small background contribution from other processes is subtracted with the help of MC simulations or sideband fits³.

The difference between the two methods is the treatment of the electrons. The Likelihood method treats the electrons from the Z decay equally and determines the probability of charge misID for each electron by minimizing a Poissonian based Likelihood function that depends on the charge misID probability. In the tag-and-probe method additional quality criteria are applied in order to define one *tag electron*⁴.

Due to the harder cuts, the probability that the charge of the tag electron was misidentified is very small and is neglected. It is assumed that the charge was correctly reconstructed. The probe electron is defined as the additional electron in events that contain a tag electron. The charge misID rate is then evaluated by:

$$\varepsilon = \frac{\text{Number of probes from SS event}}{\text{Number of probes}} \quad (7.1)$$

In general, ε is calculated in bins of p_T and $|\eta|$ since Bremsstrahlung depends on the distribution of the detector material which is not equally distributed in all directions.

Figure 7.2 shows the charge misID rates resulting from the two methods as a function of $|\eta|$ in different p_T bins. They are in good agreement within the uncertainties which include systematic and statistical uncertainties. Hence, both methods have consistent results.

The uncertainties of the Likelihood method are smaller than for the tag-and-probe method which is explained with the higher statistics in the case of the Likelihood method since the charge misID rate of both electrons is evaluated. In the tag-and-probe method only the charge misID rate of the probe is measured.

³A sideband fit estimates the number of background events outside the signal region in a control region (often one requirement of the nominal selection is inverted) assuming that those events are equally distributed in both regions. In the control region the background is expected to dominate over the signal.

⁴The quality cuts for tag electrons are listed in the Appendix C.3.3.

Finally, the charge misID rate estimated with the Likelihood method is applied to data in order to estimate the charge misID background. The difference to the misID rate evaluated by the tag-and-probe method is taken into account as a systematic uncertainty.

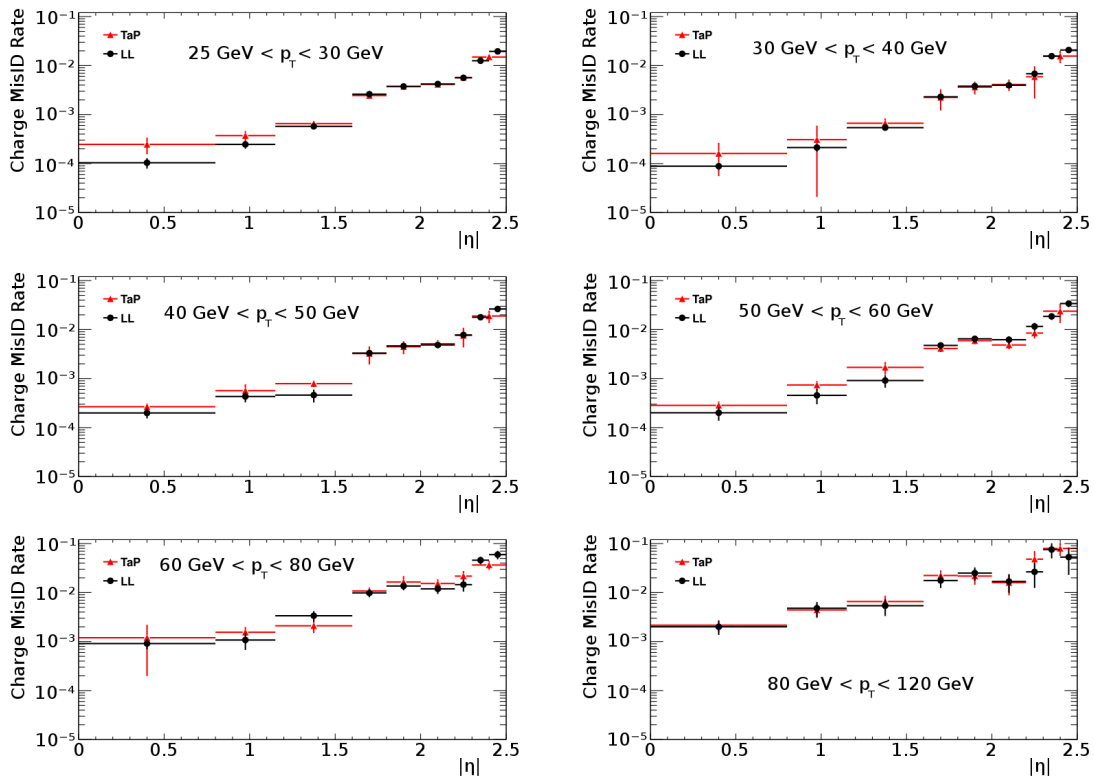


Figure 7.2: Comparison of the charge misID rates measured in data by the tag-and-probe method (red) and the likelihood method (black) in dependence of $|\eta|$ in different p_T regions [59].

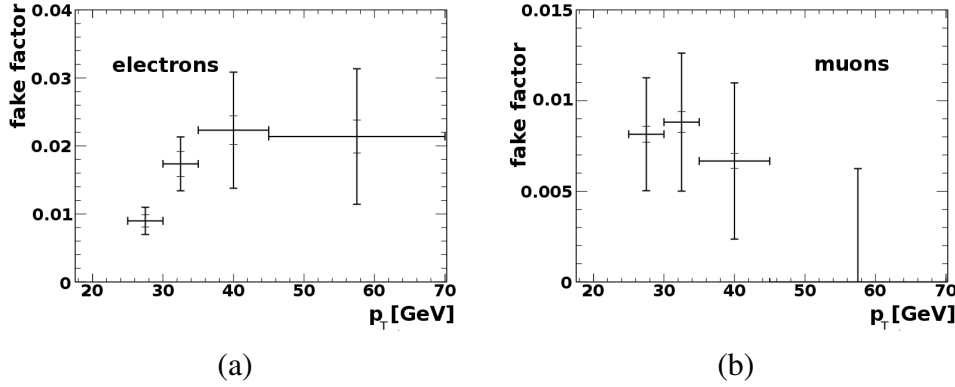


Figure 7.3: Electron and muon fake factors in dependence of the lepton p_T . The inner error bar represents the statistical uncertainty and the outer error bar the total uncertainty.

Estimation of Fake Background

All events containing one lepton from the primary vertex and one jet that is mis-reconstructed as a charged lepton contribute to the fake background. These events can pass the analysis event selection and are one of the dominant backgrounds in the $W^\pm W^\pm$ analysis with a contribution of about 14%. The main fake background sources are W +jets, $t\bar{t} \rightarrow WbWb \rightarrow \ell v b b q q$ and single top processes in which one of the produced W bosons decays leptonically to an electron or a muon. Additionally there are diboson processes where one vector boson decays leptonically and the other hadronically. However, these contribute less than the three dominant processes due to the smaller cross section of diboson production. The probability that processes contribute where two jets are reconstructed as charged leptons is very small since two isolated leptons and a large E_T^{miss} are required. Their overall proportion to the total fake background is less than 3.5%.

In order to evaluate the probability for a jet being reconstructed as a lepton from data, the *fake factor method* is used.

For the evaluation of the fake factor f_{lepton} a sample is selected where each event contains one tagging jet and one lepton which is back-to-back with the jet in the azimuthal plane. The lepton is likely to be jet faked. In this sample contributions from SM processes that produce isolated leptons should be estimated with the help of MC simulations and subtracted. However, this effect of about 13% in the fiducial phase space⁵ is neglected in this analysis. In the selected sample, f_{lepton} is evaluated from the ratio of the number of leptons that pass the tight criteria $N_{\text{tight lepton ID}}$ to the number of leptons that pass the loose criteria $N_{\text{loose lepton ID}}$:

$$f_{\text{lepton}} = \frac{N_{\text{tight lepton ID}}}{N_{\text{loose lepton ID}}} \quad (7.2)$$

and is binned in the lepton p_T . It is calculated for electrons and muons separately. Figure 7.3 shows the fake factors for electrons and muons over the lepton p_T with the corresponding statistical and systematic uncertainties.

By applying the fake factor to a sample with events containing one tight and one loose

⁵The fiducial phase will be defined in Section 7.2.2.

lepton, the number of background events in the signal region is calculated:

$$N_{\text{fake Bkg}} = f_{\text{lepton}} \cdot N_{\text{tight lepton ID} + \text{loose lepton ID}} \quad (7.3)$$

The systematic uncertainties of the fake lepton background estimation are composed of uncertainties estimated from variations in the selection of the sample from which f_{lepton} is evaluated, the difference in the quark flavour composition in the two selected samples and the subtraction of contributions with leptons from the hard interaction using MC simulations.

7.2 Object and Event Selection

All the applied selection criteria on objects or events aim to suppress the previously described backgrounds. They are defined in such a way that events with the specific $W^\pm W^\pm \text{jj}$ VBS topology pass the selection with high efficiency.

7.2.1 Object Selection

The objects used in this analysis are electrons, muons, $E_{\text{T}}^{\text{miss}}$, jets and b-jets. Their selection requirements will be described in the following.

Muons

Muon candidates are reconstructed by the STACO algorithm as combined muons (see Section 4.3). Additional kinematic cuts are applied in order to reject muons from pile-up collisions or from hadron decays. These are the following:

- The inner detector track which is associated to the muon track in the muon chambers by the STACO algorithm has to originate from the primary vertex. This is ensured by requiring the longitudinal impact parameter z_0 to be smaller than 0.5 mm and the transverse impact parameter d_0 divided by its resolution $\sigma(d_0)$ to be smaller than 3.
- The kinematic acceptance is $p_{\text{T}} > 25$ GeV.
- The muon candidate has to lie within the geometrical acceptance of the detector of $|\eta| < 2.5$.
- Isolation criteria are applied in order to reject muons from hadron decays:
 - Muons shall be isolated in the inner tracker and the muon spectrometer within a cone $\Delta R = 0.3$.
 - The sum of the p_{T} of the tracks around the muon candidate track within the cone is required to be smaller than 7% of the muon track p_{T} .
 - The sum of all energy deposits in the calorimeters around the ones of the muon candidate within the cone has to be smaller than 7% of the muon track p_{T} .

For a third lepton veto in the event selection, a slightly different muon selection is used. The main differences are a looser p_T cut of $p_T > 6$ GeV, a track isolation requirement of 0.15 times the muon track p_T , and no calorimeter isolation requirement. The full set of object selection cuts for electrons used in this analysis can be found in the Appendix C.3.1.

Electrons

In this analysis, electron candidates are reconstructed with the `tight++` quality criterion which contains requirements on the shower shape in the calorimeter, the track quality, detection of transition radiation and track-to-calorimeter-cluster matching. Additionally the following selection criteria are applied:

- The transverse energy has to be larger than 25 GeV.
- The geometrical acceptance is $|\eta| < 2.47$, excluding the transition region from the barrel to the end-cap calorimeter $1.37 \leq |\eta| \leq 1.52$.
- The isolation criteria in order to suppress secondary electrons from jets are:
 - The isolation cone size for the track and the calorimeter isolation is $\Delta R = 0.3$.
 - The sum of the p_T of the tracks around the electron candidate track within the cone is required to be smaller than 6% of the electron track p_T .
 - The sum of all energy deposits around the one of the electron cluster within the cone E_T^{cone} has to be smaller than 0.14 times the electron track p_T . Since the electron shower gets wider, the deeper it penetrates into the calorimeter, entries induced by the electron can be counted to the isolation energy. For this effect and for influences of in-time pileup, E_T^{cone} is corrected.

As in the selection of muons, a second electron selection is defined to be used in the third lepton veto. The main differences are a looser cut on the transverse energy of $E_T > 7$ GeV, the usage of the quality criterion `loose++`, a track isolation of 0.13 times the electron candidate track p_T and no calorimeter isolation requirement. The full set of object selection cuts for electrons used in this analysis can be found in the Appendix C.3.2.

Jets

Jets are reconstructed with the anti- k_T algorithm described in section 4.5. Furthermore, the candidates have to fulfill the following requirements:

- The kinematic acceptance is defined by $p_T > 30$ GeV at the hadronic energy scale
- The geometrical acceptance is $|\eta| < 4.5$
- $JVF > 0.5$ is required for jets with $|\eta| < 2.4$ and $p_T < 50$ GeV
- Jets containing b-quarks are identified by a b-tagging algorithm (MV1 tagger, $MV1 > 0.8119$) with an efficiency of 70%

After the object reconstruction, ambiguities between the objects are resolved as described in Section 4.7.

7.2.2 Event Selection

After the object selection, some event cleaning cuts are applied in order to select high quality proton-proton collision events. Events affected by detector malfunctions and read-out problems have to be removed. A so called *Good Run List* (GRL) contains the data quality status flags in all luminosity blocks of all runs. A luminosity block is a unit of time where data is taken. It has a maximum duration of 2 minutes. During the data-taking, each detector subsystems fills in flags that indicate if there were any complications. If all relevant subsystems are properly working, the luminosity blocks are marked as 'good'. The GRL has to be applied to data in order to filter only 'good' data. Additional event cleaning cuts that ensure the high quality of the events are applied. The whole list can be found in the Appendix C.2.

Fiducial Phase Space

The aQGC measurement was done in a *fiducial phase space* where the number of signal events is about the number of background events. $W^\pm W^\pm jj$ QCD is well suppressed by the VBS topology and due to the non-existence of the gluon initial state.

The fiducial phase space is defined by the following requirements:

1. Each event has to contain exactly two leptons passing the object requirement described in Section 7.2.1 with the same electric charge.
2. The p_T of both leptons has to be larger than 25 GeV
3. A Z-veto is applied in the ee-channel. It rejects all events where $|M_{ee} - M_Z| < 10$ GeV, with M_{ee} being the invariant mass of the electron-system. This requirement suppresses the charge misID background.
4. The invariant mass of the two leptons M_{ll} has to be larger than 20 GeV. Since Drell-Yan processes⁶ are not well modeled by simulation in the low mass region, this cut reduces the corresponding uncertainty.
5. It is possible that the event contains additional leptons that do not pass the object selection. These can result from background processes that have more than two leptons in the final state like WZ and ZZ or from photons radiated from muons and together being reconstructed as electrons. This background is suppressed by a third lepton veto where looser quality cuts are applied on the lepton. These object requirements were outline in Section 7.2.1.
6. A cut on $E_T^{\text{miss}} > 40$ GeV is applied which accounts for the neutrinos in the final state. It further reduces background from charge misidentification like $Z+jets$.
7. Two or more jets with $p_T > 30$ GeV and $|\eta| < 4.5$ have to be present in each event.
8. The b-jet veto rejects each event where at least one of the selected jets is tagged as a b-jet (see Section 4.5). The probability of b-tagging one of the jets in a signal event is

⁶The term *Drell-Yan* denotes the annihilation of a quark and an anti-quark resulting in the production of a virtual photon γ^* or a Z boson that decays into two leptons [64].

very small since in this channel a final state b-quark can only be produced by an initial state top quark that radiates a W boson. The probability that a top quark occurs in a proton of an energy of 4 TeV is negligibly small.

9. The two highest p_T jets in the event are defined as tagging jets. They are required to have an invariant mass of $M_{jj} > 500$ GeV and a difference in rapidity of $\Delta Y_{jj} = |Y_{j1} - Y_{j2}| > 2.4$.

7.3 Cross Section Extraction

Measuring the $W^\pm W^\pm jj$ process means measuring its cross section in a defined phase space. Since the selection efficiencies in the three channels are different, they have to be treated independently in order to get the maximum sensitivity. For one channel the fiducial cross section σ_{fid} can be extracted by

$$\sigma_{\text{fid}} = \frac{N - B}{L \cdot \varepsilon} \quad (7.4)$$

with N being the number of observed events, B the number of expected background events, L the integrated luminosity and ε the efficiency.

The efficiency is defined as the ratio of events in the signal region at reco level over the number of events in the fiducial phase space at truth level (the terms reco and truth level were defined in Section 5.1):

$$\varepsilon = \frac{N_{\text{fid}}(\text{reco level})}{N_{\text{fid}}(\text{truth level})}. \quad (7.5)$$

The selection of the fiducial phase space on truth level is done by the same kinematic requirements as presented in Section 7.2.2. However, the Z -veto in the ee -channel is omitted in order to treat the three channels equally and events where at least one of the W bosons decays into a tau and a neutrino are vetoed. On reco level $W \rightarrow \tau \nu$ events are included since a distinction is difficult. From MC simulations, their contribution to the total number of events in the fiducial phase space was evaluated to be around 10%.

The number of signal events S can be evaluated from σ_{fid} by

$$S = \varepsilon \cdot \sigma_{\text{fid}}. \quad (7.6)$$

The cross section measurement has an uncertainty that results from the uncertainties of the variables used for its calculation in Equation 7.4. The efficiency has an uncertainty from the statistical and systematic uncertainties of the $W^\pm W^\pm jj$ EW prediction, B has an uncertainty coming from the systematic and statistical uncertainty of the background prediction and the measurement of the luminosity has an uncertainty as well. N is measured and has only a statistical uncertainty associated.

All systematic uncertainties are described in the following section.

7.4 Systematic Uncertainties

Systematic uncertainties in the MC driven signal and background predictions are estimated mainly from variations applied to the MC samples. Some of them were outlined in Section 5.2. The systematic uncertainties of the data driven methods were explained in Section 7.1.2.

Summarizing these preceding discussions, the following sources were considered in the systematic uncertainties in the $W^\pm W^\pm jj$ analysis:

- the scale factor of the b-tagging algorithm (b-tag SF),
- the b-jet mis-modeling of the event generator SHERPA,
- the trigger scale factor (Trigger SF),
- the electron and muon reconstruction efficiency, energy, and resolution variations (e-reco and μ -reco)
- the energy and resolution variations of leptons was propagated to E_T^{miss} ,
- the calculation of the theoretical fiducial cross section: Here, systematic uncertainties result from missing higher order QCD corrections, PDF and α_s uncertainties, the choice of the renormalization and factorization scale, and parton shower effects,
- the variation of the jet energy scale (JES)
- the variation of the jet energy resolution (JER),
- the variation of the modeling of the JVF in MC samples,
- the pile-up reweighing in MC simulations (Pile-Up),
- the charge flip factors (CF Rate),
- the fake rates of the fake background estimation,
- the conversion rate of photons into electron pairs: These are not well modeled in MC simulations. A measure how much the photon conversions differ from the observation is provided by the level of agreement between data and MC in charge misidentification rates,
- and the subtraction of prompt leptons within the fake factor evaluation⁷

The influence of these sources of uncertainties on the event yields were evaluated by varying the corresponding correction factors up and down within their 1σ uncertainties. The difference to the nominal selection is given in Table 7.2 in % for each source and background contribution.

⁷Events in the dijet sample that contain one real lepton, are subtracted using MC simulations of W +jets and Z +jets. The low $\Delta\phi(1,j)$ region is not well modeled in those MC samples. Therefore, a factor is applied which scales them to data.

Source	$W^\pm W^\pm$ jj EW	$W^\pm W^\pm$ jj QCD	WZ	$t\bar{t}+V$	ZZ	$W\gamma$	Fakes	CF
b-tag SF	2.2/2.4/2.1		2.8/3.0/5.5	19.1/19.1/19.1	2.0/3.2/6.7	2.4/2.4/2.4	–	–
b-jet Mismodelling	0.2/0.2/0.2	–	3.5/3.5/3.5	–	–	–	–	–
e -reco		2.4/1.2/0.0			2.6/1.3/0.0	2.4/1.2/0.0	–	–
μ -reco			0.0/0.3/0.6				–	–
Trigger SF			0.1/0.25/0.55				–	–
E_T^{Miss}	1.0/0.3/0.3		1.8/1.8/1.8	6.4/6.4/6.4	27.3/27.3/27.3	14.0/14.0/14.0	–	–
JER	1.0/1.0/1.0		1.5/1.5/1.5	–	1.5/1.5/1.5	–	–	–
JES	$^{+4.5}_{-4.0}/\pm^{+4.5}_{-4.0}$		$^{+13.3}_{-16.9}/\pm^{+13.3}_{-16.9}$	25.5/25.5/25.5	$^{+13.2}_{-15.5}/\pm^{+13.2}_{-15.5}$	30/30/30	–	–
JVF	$^{+0.3}_{-0.0}/\pm^{+0.3}_{-0.0}$		$^{+1.2}_{-0.0}/\pm^{+1.2}_{-0.0}$	–	$^{+1.2}_{-0.0}/\pm^{+1.2}_{-0.0}$	–	–	–
Theory	9.0/9.0/9.0	16.0/16.0/16.0	11.0/11.0/11.0	30.0/30.0/30.0	19.0/19.0/19.0	17.0/17.0/17.0	–	–
Conversions			–			$^{+22}_{-13}/\pm^{+22}_{-13}$	–	–
Pileup	0.5/0.5/0.5	1.5/1.5/1.5	8.0/8.0/8.0	1.5/1.5/1.5	8.0/8.0/8.0	8.0/8.0/8.0	–	–
Luminosity			2.8/2.8/2.8				–	–
CF Rate/E corr.				–			16/35/0.0	
Fake Rate				–			36/38/51	–
Prompt Subtract.				–			7.0/3.5/0.6	–

Table 7.2: Summary of systematic uncertainties in the fiducial phase space. They are separated into the three analysis channels which are separated by slashes: ee/em/mm

Process	ee-channel	em-channel	mm-channel	combined
$W\gamma$	$0.49 \pm 0.29 \pm 0.21$	$1.06 \pm 0.39 \pm 0.45$	-	$1.55 \pm 0.49 \pm 0.50$
Charge Flip	$1.41 \pm 0.16 \pm 0.21$	$0.66 \pm 0.09 \pm 0.22$	-	$2.07 \pm 0.18 \pm 0.30$
Fake Background	$0.64 \pm 0.11 \pm 0.22$	$1.66 \pm 0.18 \pm 0.56$	$0.30 \pm 0.05 \pm 0.15$	$2.59 \pm 0.22 \pm 0.62$
ZZ	$0.04 \pm 0.03 \pm 0.01$	$0.05 \pm 0.03 \pm 0.02$	$0.01 \pm 0.00 \pm 0.00$	$0.10 \pm 0.04 \pm 0.02$
WZ	$1.64 \pm 0.18 \pm_{0.43}^{0.38}$	$3.62 \pm 0.24 \pm_{0.91}^{0.80}$	$1.35 \pm 0.16 \pm 0.01$	$6.61 \pm 0.34 \pm_{1.06}^{0.93}$
$W^\pm W^\pm jj$ QCD	$0.37 \pm 0.04 \pm 0.05$	$0.92 \pm 0.05 \pm 0.13$	$0.52 \pm 0.04 \pm 0.07$	$1.81 \pm 0.08 \pm 0.16$
TTbar+V	$0.02 \pm 0.01 \pm 0.03$	$0.05 \pm 0.01 \pm 0.05$	$0.02 \pm 0.01 \pm 0.01$	$0.09 \pm 0.02 \pm 0.06$
total Background	$4.62 \pm 0.40 \pm 0.55$	$8.02 \pm 0.50 \pm 1.15$	$2.19 \pm 0.17 \pm 0.35$	$14.82 \pm 0.66 \pm 1.32$
$W^\pm W^\pm jj$ EW	$2.61 \pm 0.14 \pm 0.19$	$8.07 \pm 0.25 \pm 0.56$	$4.12 \pm 0.18 \pm 0.32$	$11.26 \pm 0.34 \pm 0.67$
total predicted	$7.23 \pm 0.42 \pm 0.58$	$16.08 \pm 0.56 \pm 1.28$	$6.31 \pm 0.25 \pm 0.48$	$26.08 \pm 0.75 \pm 1.48$
observed	6.00	18.00	8.00	32

Table 7.3: Summary of expected and observed event yields after all cuts with the corresponding statistical (first) and systematic (second) uncertainties.

7.5 Results of Cross Section Measurement

Table 7.3 summarizes the predicted event yields for the signal and various background contributions and the number of observed events after all cuts in all three channels. The estimated number of events is about 6 events smaller than the observed number. This corresponds to an agreement of the prediction and the observation within 1σ .

The measured cross section is obtained from a Likelihood function where Equation 7.4 is implemented for each channel and the uncertainties are included as Gaussian constraints⁸. The number of selected events, the predicted background and the systematic uncertainties [59] gives a best estimate of the total cross section:

$$\sigma_{\text{fid,obs}}^{W^\pm W^\pm jj \text{ EW}} = 1.41 \pm_{0.47}^{0.56} \text{ fb.} \quad (7.7)$$

The expected value gained from theory is

$$\sigma_{\text{fid,exp}}^{W^\pm W^\pm jj \text{ EW}} = 0.88 \pm 0.07 \text{ fb.} \quad (7.8)$$

The $W^\pm W^\pm jj$ EW process has been observed with a 3.4σ significance [59].

The given uncertainties for the observation combine the statistical and systematic uncertainties whereas the statistical uncertainty is about a factor of 2 larger than the systematic. The given expected cross section neglects the interference between the EW and the QCD $W^\pm W^\pm jj$ production which is an effect of about 7%. It would increase the expected cross section to a value of 0.95 fb. The measured cross section includes the interference terms since the purely EW process and the interference process cannot be separated in the measurement.

Using the delta log Likelihood method⁹, an expected and an observed 95% CL upper limit

⁸See Section 7.8 for the description of the statistical method.

⁹The delta log Likelihood method will be explained in section 7.8.1.

on the cross section, $\sigma_{\text{fid}}^{\text{UL}}$, can be determined. It was evaluated to be 2.2 times the predicted $W^\pm W^\pm \text{jj}$ EW cross section when fitting the Likelihood function to the Asimov data set (expected upper limit) and to be 1.8 times the observed fiducial cross section when fitting to the observed data (observed upper limit):

$$\sigma_{\text{fid,exp}}^{\text{UL}} = 2.2 \cdot \sigma_{\text{fid,exp}}^{W^\pm W^\pm \text{jj}} \quad (7.9)$$

$$\sigma_{\text{fid,obs}}^{\text{UL}} = 1.8 \cdot \sigma_{\text{fid,obs}}^{W^\pm W^\pm \text{jj}} \quad (7.10)$$

All cross sections larger than the upper limit cross section are excluded from being compatible with the fitted data at 95% confidence.

7.6 Signal Samples and Cross Sections

The focus of this work lies on the measurement of the aQGC parameters α_4 and α_5 which were introduced in Section 2.3.2. Therefore, MC samples have been produced and cross sections have been determined for different values of these parameters. In this section, the dependence of the cross section on aQGC parameters and some kinematic distributions shall be discussed in order to work out the differences between the SM process and the aQGC scenario.

7.6.1 Official WHIZARD Signal Samples

The signal samples were generated in a wider phase space than the fiducial phase space in order to allow for migration of events into the extended phase space due to the parton shower or detector effects. For this purpose the event generator WHIZARD was used, where the aQGC model presented in section 2.3 is implemented.

WHIZARD Phase Space

The following requirements were imposed on the produced events:

- The quarks are required to be isolated from each other by $\Delta R_{jj} > 0.4^{10}$.
- Leptons and quarks have to have $|\eta| < 5$.
- Jets are required to have p_T larger than 15 GeV.
- Leptons are required to have p_T larger than 8 GeV.

For all produced samples the factorization scale was set to the partonic center of mass energy $\sqrt{\hat{s}}$. For each generation, different coupling strengths α_4 and α_5 were used with $\alpha_4 = \alpha_5 = 0$ representing the SM case. The events were showered with PYTHIA and then fed into the full detector simulation. Table 7.4 lists the WHIZARD samples which were officially produced

¹⁰Here, j indicates quarks which are in the final output of WHIZARD. They become jets in the showering process (see Section 5.1).

Dataset ID	α_4	α_5	σ_{fid} [fb]	ε [%]
147513	0.0	0.0	0.666	62.8
185146	0.0	0.05	0.784	66.4
185147	0.05	0.0	0.951	68.4
185148	0.05	0.05	1.190	68.2
185142	0.0	0.1	1.022	67.3
185143	0.1	0.0	1.348	71.1
147515	0.1	0.1	1.932	71.4
147514	0.0	0.2	1.588	70.9
147516	0.2	0.0	2.271	73.3
147517	0.2	0.2	3.514	72.2
185144	0.1	0.2	2.578	72.6
185145	0.2	0.1	2.858	72.6

Table 7.4: Summary of officially produced WHIZARD samples for different aQGC parameters, the corresponding fiducial cross sections (see Section 7.6.2) and efficiencies.

and their corresponding efficiencies. The efficiency in dependence of the aQGC parameters are shown also in Figure 7.5(a). The uncertainty due to the sample statistics is 8.1% for the SM case and decreases with increasing aQGC parameters to 5.1% for $\alpha_4 = \alpha_5 = 0.2$. The points (α_4, α_5) for which no samples were produced are interpolated bilinearly. In this work, constraints on α_4 and α_5 are only determined in the first quadrant of the plane, i.e. for positive values of the aQGC parameters.

7.6.2 Cross Sections of aQGC Scenarios

Additionally WHIZARD is used to calculate $W^\pm W^\pm jj$ EW cross sections in the extended phase space, which will be defined below, on a smaller α_4 - α_5 -grid than the produced samples are given. Here, a different factorization scale was used which is two times the W boson mass $2M_W$. A step width of 0.02 for $\alpha_4 \in [-0.2, 0.2]$ and $\alpha_5 \in [-0.2, 0.2]$ was chosen.

Figure 7.4 illustrates the cross section in the α_4 - α_5 -plane. The elliptic form of the contours indicates a destructive interference between the two operators $\mathcal{L}_4$ and $\mathcal{L}_5$ for opposite signed couplings. For the aQGC parameter measurement only the first quadrant is considered in this work.

In order to compare the extended cross sections with fiducial cross sections, they have to be interpolated to the fiducial phase space by multiplying the acceptance A .

Acceptance Calculation

The acceptance A is defined as the fraction of simulated events in the extended phase space that fulfill the requirements of the fiducial phase space on truth level:

$$A = \frac{N_{\text{fid}}(\text{truth level})}{N_{\text{ext}}(\text{truth level})}. \quad (7.11)$$

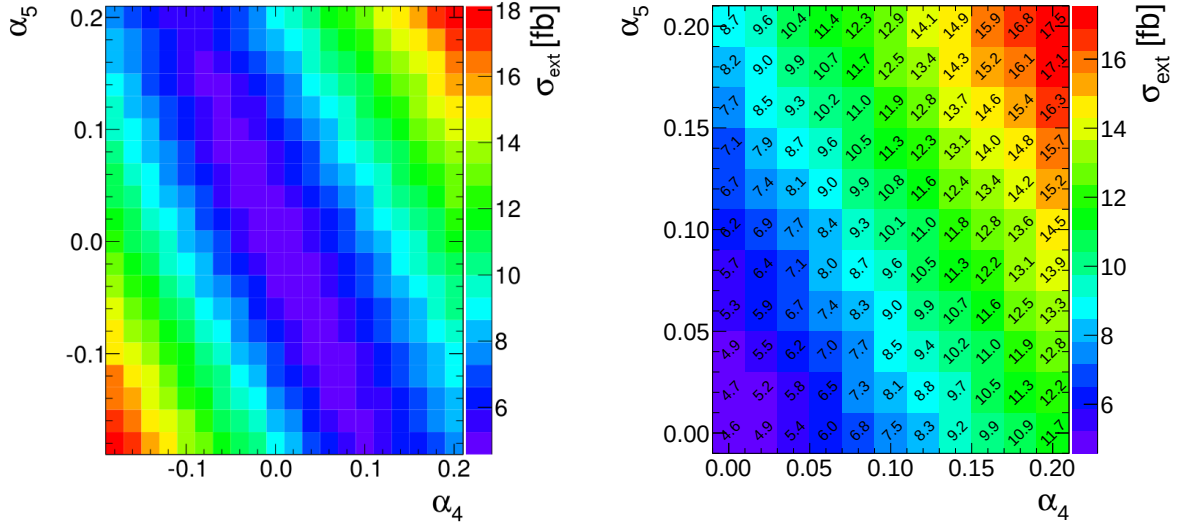


Figure 7.4: Cross section dependence in the extended phase space on α_4 and α_5 . On the left, all four quadrants are shown and on the right a zoom into the first quadrant (positive α_4 and α_5) which is the region where the constraints on the couplings will be set, is presented.

Hence, a cross section that was calculated in the extended volume can be translated into a cross section in the fiducial volume by

$$\sigma_{\text{fid}} = A \cdot \sigma_{\text{ext}}. \quad (7.12)$$

The definition of the fiducial phase space on truth level was given in Section 7.2.2.

Extended Phase Space

The extended phase space is defined by the following requirements:

- Events where at least one W boson decays into a tau-lepton and a tau-neutrino are discarded.
- Each event contains two equally charged leptons with $p_T > 10$ GeV and $|\eta| < 5$.
- At least two jets with $p_T > 20$ GeV and $|\eta| < 5$ are present.
- The invariant mass of the two highest p_T jets is required to be above 150 GeV.

Figure 7.5 (b) shows the calculated acceptances in the α_4 - α_5 -plane. The uncertainties resulting from the MC statistics is 2.0% for the SM point and decreases with increasing aQGC parameters to 2.6% for the point $\alpha_4 = \alpha_5 = 0.2$. For aQGC parameter points (aQGC points) where no samples were produced, the acceptances are interpolated bilinearly.

With increasing coupling parameters, A increases. This indicates that the selection is well adapted for an aQGC measurement.

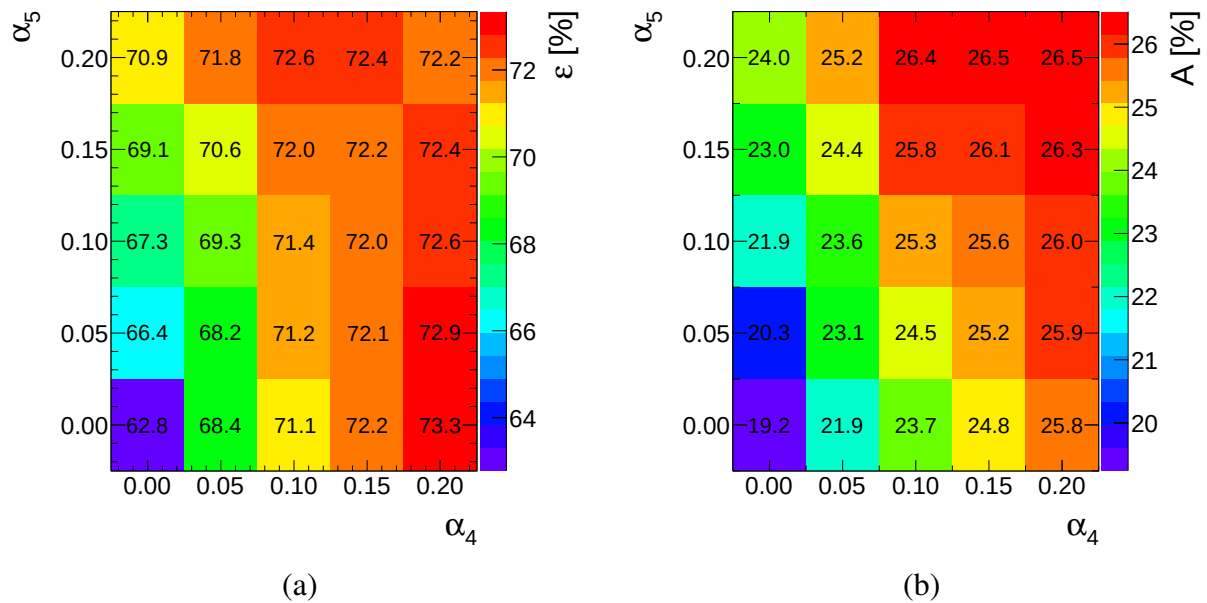


Figure 7.5: Dependence of the efficiency (a) and the acceptance (b) on α_4 and α_5 . The bin contents correspond to the aQGC parameter values in the bin centers. The points for which no official samples were produced, are interpolated bilinearly.

Next to Leading Order Correction

All calculations done with WHIZARD are at LO in QCD and EW. A NLO QCD event generator is POWHEGBOX [65]. Using this generator the cross section of $W^\pm W^\pm jj$ EW for the SM case has been evaluated in the fiducial phase space again:

$$\sigma_{\text{fid}}^{\text{NLO}} = 0.881 \text{ fb.} \quad (7.13)$$

This result is trusted more since the calculations are more precise when NLO corrections are taken into account. Therefore, a correction factor k is evaluated that scales the LO fiducial cross sections gained from WHIZARD to $\sigma_{\text{fid}}^{\text{NLO}}$:

$$k = \frac{\sigma_{\text{fid}}^{\text{NLO}}}{\sigma_{\text{LO}}} = 1.32. \quad (7.14)$$

This k -factor is assumed to be aQGC independent and is therefore applied to the cross sections of all WHIZARD samples. Figure 7.6 shows the cross sections in the fiducial phase space of Section 7.2.2 in the first quadrant of the α_4 - α_5 -plane. The k -factor and a factor of 4/9 which excludes the contribution where one or both W bosons decay to taus and neutrinos are applied. The interference between $W^\pm W^\pm jj$ EW and QCD is neglected.

These fiducial cross sections will be used in the aQGC measurement in Section 7.9.

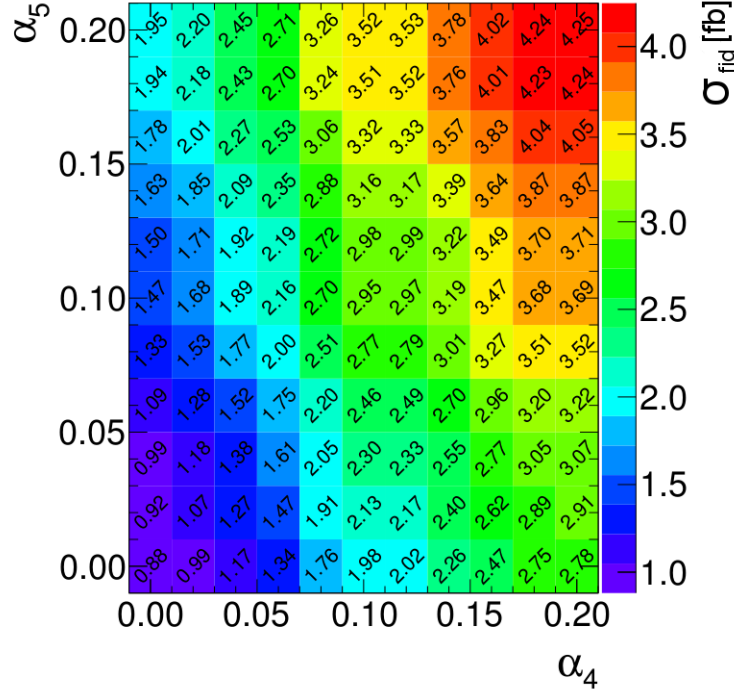


Figure 7.6: Fiducial cross sections in dependence on α_4 and α_5 . The scale factor $k = 1.32$ has been applied to all aQGC parameter points.

7.6.3 Exclusion of aQGC Cross Sections

In order to determine whether a $W^\pm W^\pm jj$ EW cross section where aQGC are present, is compatible with the data, the number of expected events in the fiducial phase space in the presence of aQGC has to be compared to the number of $W^\pm W^\pm jj$ EW SM events that corresponds to the upper limit cross section presented in Section 7.5. Using Equation 7.6, each aQGC point can be excluded for which

$$\epsilon_{\text{aQGC}} \cdot \sigma_{\text{fid}}^{\text{aQGC}} \geq \epsilon_{\text{SM}} \cdot \sigma_{\text{fid}}^{\text{UL}} \quad (7.15)$$

is true, with ϵ_{QGC} being the efficiency of the specific aQGC point, $\sigma_{\text{fid}}^{\text{aQGC}}$ its fiducial cross section and ϵ_{SM} the efficiency of the SM WHIZARD sample. Using this formula, the upper limit cross section can be translated into confidence intervals in α_4 and α_5 .

7.7 Variables Sensitive to aQGC

Kinematic variables that are sensitive to aQGC can be recognized by comparing the corresponding distribution of $W^\pm W^\pm jj$ EW to the distribution of the SM process. The distribution of the ratio between the case, where aQGC are present, and the SM gives indications in which region the sensitivity is high. Those kinematic regions can be selected in order to optimize the aQGC measurement. In general, variables that reflect the kinematic relation of the two leptons to each other are well suited since the scattering process results in correlated

lepton kinematics. But also the jet kinematics change in the presence of aQGC.

Figure 7.7 shows the distributions of the absolute azimuthal angle between the jets $\Delta\phi_{jj}$, the invariant mass of the jets M_{jj} and the absolute difference between the jet rapidities ΔY_{jj} . In the left column, different aQGC points (α_4, α_5) (colored lines) are compared to the SM (black line) and in the bottom, the ratio between the aQGC point $\alpha_4 = \alpha_5 = 0.1$ and the SM case is shown. It will be referred to as *aQGC-SM-ratio* in the following. For these plots the officially produced WHIZARD samples were used (see Section 7.6.1) which were scaled to the same cross section before the event selection. All cuts up to the $N_{\text{jets}} \geq 2$ cut in the selection of the fiducial phase space (point seven in Section 7.2.2) are applied. Hence, the areas beneath the curves are a measure for different sample acceptances and efficiencies in this selection. In order to scale the aQGC distributions to a luminosity of 20.28 fb^{-1} factors between 36 (SM) and 15 (0.2,0.2) have to be applied.

In the right column, the distributions of the background divided in the different contributions and scaled to a luminosity of 20.28 fb^{-1} , are shown. Like the aQGC distributions on the left all background distributions were created after the $N_{\text{jets}} \geq 2$ cut in the selection of the fiducial phase space (point seven in Section 7.2.2).

Figure 7.8 shows the corresponding diagrams for the lepton variables $\Delta\phi_{ll}$ and M_{ll} and the scalar sum of the transverse momenta of the leptons

$$\sum p_T^{\text{ll}} = |\mathbf{p}_T^{\text{l}_1}| + |\mathbf{p}_T^{\text{l}_2}| \quad (7.16)$$

The following conclusions can be drawn:

- The **distribution of $\Delta\phi_{jj}$** shows a higher amount of aQGC events than SM events for small values. The aQGC-SM-ratio takes values of up to 2.6 for small $\Delta\phi_{jj}$. The background, however, has a similar shape as the aQGC signal. Hence, when cutting on this variable, the distinction between the signal and the background is not improved.
- The **M_{jj} distribution** of $W^\pm W^\pm jj$ EW shows as peak at $\sim 80 - 90 \text{ GeV}$ which corresponds to the W and Z boson masses. This peak results from triboson production¹¹. Since this is a background process in this analysis, events with $M_{jj} < 150 \text{ GeV}$ have to be excluded.

The aQGC-SM-ratio is rather constant over the plotted region. Therefore, we can conclude that this variable is not well suited for discriminating between the SM and the aQGC topology. However, the distinction between the signal and the background is improved when selecting only events with high M_{jj} since the background decreases by a factor of 4 in the region between 400 and 800 GeV and the aQGC signal decreases only by a factor of 1.5.

- The **ΔY_{jj} distribution** of $W^\pm W^\pm jj$ EW shows two maxima, one at ~ 0.5 and one at ~ 3 in the SM case. The former results from the triboson production with one boson decaying hadronically which induces the peak at $\sim 80 - 90 \text{ GeV}$ in the M_{jj} signal distribution as well. The resulting jets are nearly collinear and the peak at ~ 0.5 is an artifact from the jet clustering algorithm where the cone size was chosen to be

¹¹Two equally charged W bosons and one additional vector boson that decays hadronically

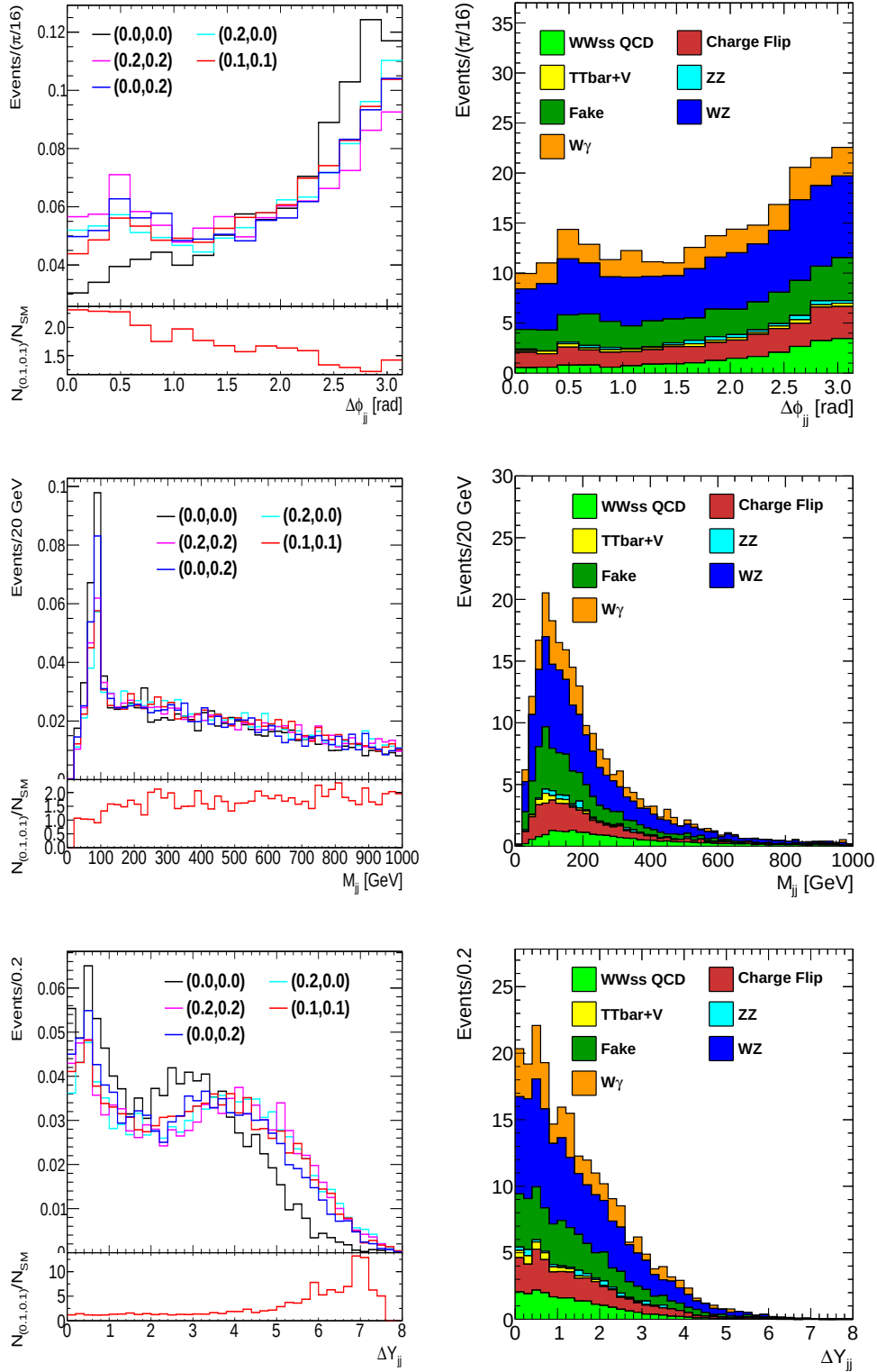


Figure 7.7: Distributions of jet kinematic variables after the $N_{\text{jets}} \geq 2$ cut in the selection of the fiducial phase space (point seven in Section 7.2.2). The left column $W^\pm W^\pm$ EW shows different aQGC parameter scenarios scaled to the same cross section before the event selection (see text for more details). The diagram beneath contains the ratio between the number of events of for $\alpha_4 = \alpha_5 = 0.1$ and the number of SM events in each bin. The right column shows the background distributions divided into the different sources and scaled to an integrated luminosity of $\int L dt = 20.281 \text{ fb}^{-1}$.

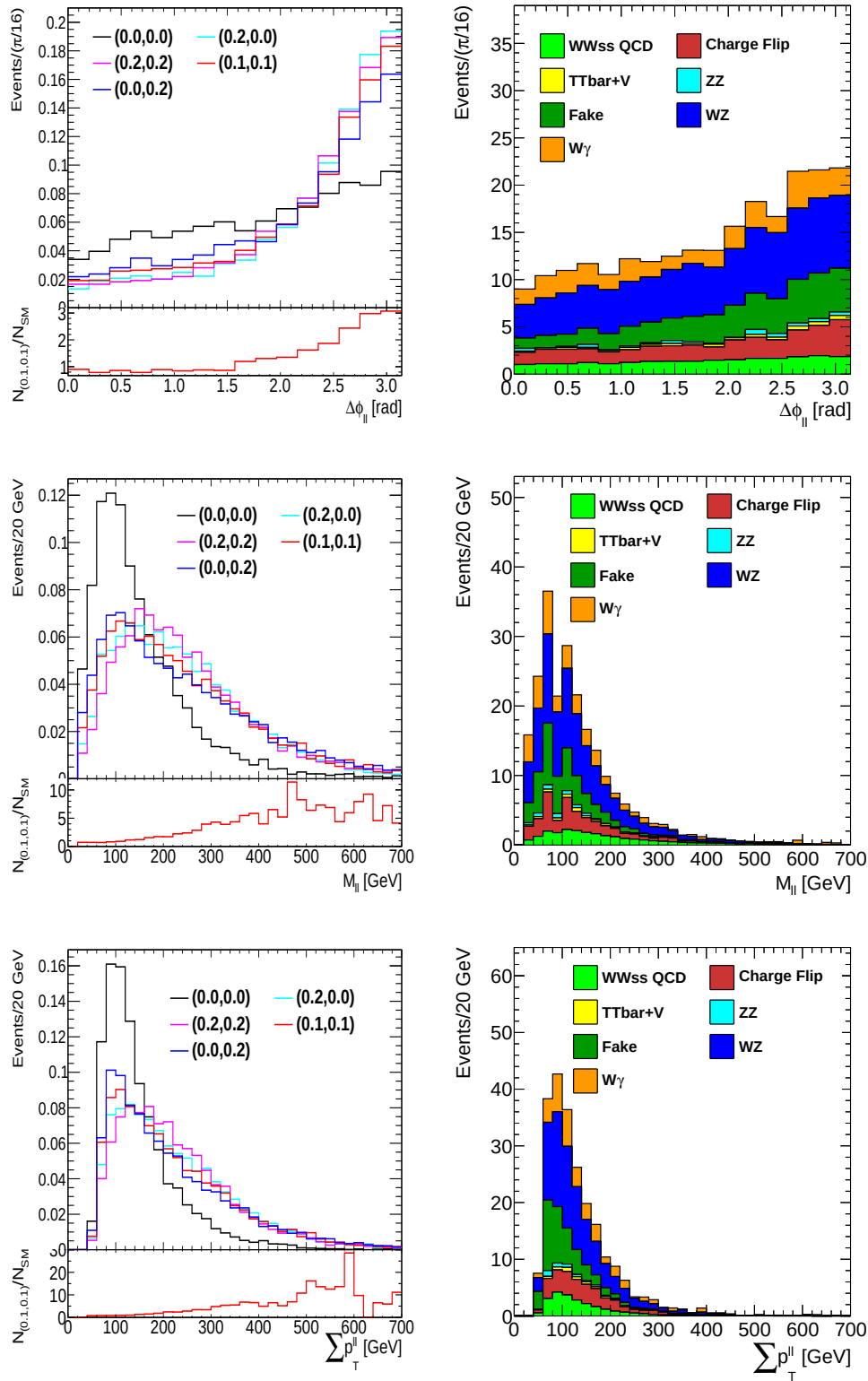


Figure 7.8: Distributions of interesting lepton kinematic variables after the $N_{\text{jets}} \geq 2$ cut in the selection of the fiducial phase space (point seven in Section 7.2.2). In the left column $W^\pm W^\pm jj$ EW for different aQGC parameters scaled to the same cross section before the event selection are shown (see text for more details). The diagram beneath contains the ratio between the number of events of for $\alpha_4 = \alpha_5 = 0.1$ and the number of SM events in each bin. The right column shows the background distributions divided into the different sources and scaled to an integrated luminosity of $\int L dt = 20.281 \text{ fb}^{-1}$.

$R = 0.4$. The peak would be shifted if a different jet cone parameter had been used. The maximum at ~ 3 results from the VBS topology with the two forward tagging jets that are well separated in Y . In the presence of aQGC, the maximum is shifted to higher ΔY_{jj} which can be explained by an increase of high energetic processes.

The aQGC-SM-ratio is constant for small ΔY_{jj} with a value of 2 up to $\Delta Y_{jj} = 5$ and takes values of up to 8 for $\Delta Y_{jj} > 6$.

The shape of the background distribution is completely different from the signal since in general, jets resulting from QCD processes are less separated in rapidity.

Hence, a cut on this variable is very well suited to distinguish between $W^\pm W^\pm jj$ EW SM signal process and $W^\pm W^\pm jj$ aQGC, and between the signal and the background.

- The **distribution of $\Delta\phi_{ll}$** shows a peak at π for all aQGC points which in fact becomes larger with increasing couplings. The ϕ coordinates of the two charged leptons are correlated since the W bosons tend to be more back to back and more boosted in the presence of aQGC. This results in an increase of the aQGC-SM-ratio in the high $\Delta\phi_{ll}$ region up to a value of 3.

The background shows a similar shape as the signal and starts to increase at the same point in $\Delta\phi_{ll}$ as the point where the difference between SM and aQGC signal becomes larger. However, the background increases over the whole $\Delta\phi_{ll}$ region by a factor of 2 and the aQGC signal by a factor of 5-9. Hence, a cut on this variable can increase the sensitivity to aQGC.

- The **M_{ll} distribution** shows a strong sensitivity to the presence of aQGC. The peak at ~ 100 GeV in the SM signal distribution is shifted to higher energies with increasing coupling strengths. This indicates that in the aQGC case the W bosons scatter with higher energies. Therefore, the tail of M_{ll} distributions for aQGC is longer than for the SM as well. The aQGC-SM-ratio increases for high M_{ll} and reaches values of up to 10. The drop of the number of background events at $M_{ll} \sim 90$ GeV results from the Z-veto in the ee-channel. The background distribution has a similar shape as the signal distribution for the SM case. However, it is different compared to the signal if aQGC are present. Hence, a cut on M_{ll} is well suited to increase the sensitivity to aQGC.
- The signal and background **distributions of $\sum p_T^{ll}$** show the same dependence as the corresponding M_{ll} distributions which can be explained by the strong correlation of these two variables. Correlations will be discussed in the remainder of this section.

Concluding the discussion, a cut on M_{jj} has good capabilities to distinguish between the signal and the background, a cut on ΔY_{jj} , $\Delta\phi_{ll}$, M_{ll} , and $\sum p_T^{ll}$ to distinguish between a SM signal and an aQGC signal and to suppress the background if the signal contains aQGC. $\Delta\phi_{jj}$ is not very sensitive to aQGC since the aQGC-SM-ratio is rather small and the shapes of the signal and the background distributions are very similar.

Imposing appropriate requirements on these variables can improve the aQGC measurement. However, due to correlations it is not reasonable to set cuts on all of them.

Table 7.5 lists the correlation coefficients¹² for the aQGC scenario $\alpha_4 = \alpha_5 = 0.1$ and the

¹²The definition of the correlation coefficient is given in the Appendix B.1

	SM	$\alpha_4 = \alpha_5 = 0.1$		SM	$\alpha_4 = \alpha_5 = 0.1$
$\Delta\phi_{jj}-\Delta\phi_{ll}$	-0.01	0.00	$\Delta\phi_{ll}-M_{jj}$	0.00	-0.08
$\Delta\phi_{jj}-\sum p_T^{ll}$	-0.15	-0.13	$\Delta\phi_{jj}-M_{ll}$	-0.12	-0.09
$\Delta Y_{jj}-\sum p_T^{ll}$	-0.01	0.10	$\Delta\phi_{jj}-\Delta Y_{jj}$	-0.07	0.22
$\Delta Y_{jj}-M_{jj}$	0.71	0.69	$M_{ll}-M_{jj}$	0.06	-0.00
$\Delta\phi_{jj}-M_{jj}$	0.45	0.27	$\Delta Y_{jj}-\Delta\phi_{ll}$	0.17	-0.01
$\Delta\phi_{ll}-M_{ll}$	0.34	0.45	$M_{jj}-\sum p_T^{ll}$	0.07	0.09
$\sum p_T^{ll}-M_{ll}$	0.68	0.80	$M_{ll}-\Delta Y_{jj}$	0.14	-0.03
$\sum p_T^{ll}-\Delta\phi_{ll}$	0.18	0.37			

Table 7.5: Summary of the correlation coefficients of all combinations of the introduced kinematic variables. The two dimensional distributions for the combinations in the left table can be found in Figure 7.9

SM case. Figure 7.9 shows examples of two dimensional distributions which show a correlation. They were produced from the WHIZARD sample $\alpha_4 = \alpha_5 = 0.1$ after the $N_{\text{jets}} \geq 2$ requirement in the selection of the fiducial phase space (point seven in Section 7.2.2) .

In general, the correlations between lepton variables seem to increase in the presence of aQGC whereas the correlations between jet variables decrease. Comparing lepton variables to jet variables the correlations are negligible for the SM case as well as for the presence of aQGC. In VBS, the lepton kinematic is influenced by the boson kinematic which results from the scattering process. However, the boson kinematic after the scattering is not related to the jet kinematic any more.

Comparing jet variables to jet variables and lepton variables to lepton variables, stronger correlations exist. The 2D distributions of $\sum p_T^{ll}-M_{ll}$ and $\Delta Y_{jj}-M_{jj}$ show strong correlations. The former can be explained by the fact that the leptons prefer a high angular separation in ϕ . The latter results from the jet topology in VBS. The more the two jets are in the forward direction and hence, separated in rapidity, the less they were diverted by the radiation of the W bosons and hence, the less energy was transferred to the bosons.

$\sum p_T^{ll}$ and $\Delta\phi_{ll}$ seem to be partially correlated. A strong correlation between $\sum p_T^{ll}$ and $\Delta\phi_{ll}$ is only present for $\Delta\phi_{ll} > 2$. If the W bosons are high energetic they are more back to back (high $\Delta\phi$) and tend to have high transverse momenta. Hence these two variables are connected. This kinematic is transferred to the leptons for highenergetic bosons due to a Lorentz boost. For lower energetic bosons the decay products are more deviated from the direction of the mother particle. A similar behavior can be seen in the 2D distribution of M_{ll} and $\Delta\phi_{ll}$ for which the same arguments hold since $\sum p_T^{ll}$ and M_{ll} are strongly correlated.

We can draw the conclusion that M_{jj} and ΔY_{jj} are strongly correlated for the signal process. However, a cut on both variables is reasonable nevertheless since both have good background reduction capabilities and ΔY_{jj} discriminates well between a SM and an aQGC signal. M_{ll} and $\sum p_T^{ll}$ have strong correlations and similar shapes in the signal and background distributions. Therefore, only cuts on $\sum p_T^{ll}$ shall be investigated. $\Delta\phi_{ll}$ and $\sum p_T^{ll}$ are only slightly correlated which is why the influence of cuts on both variables on the aQGC measurement shall be studied.

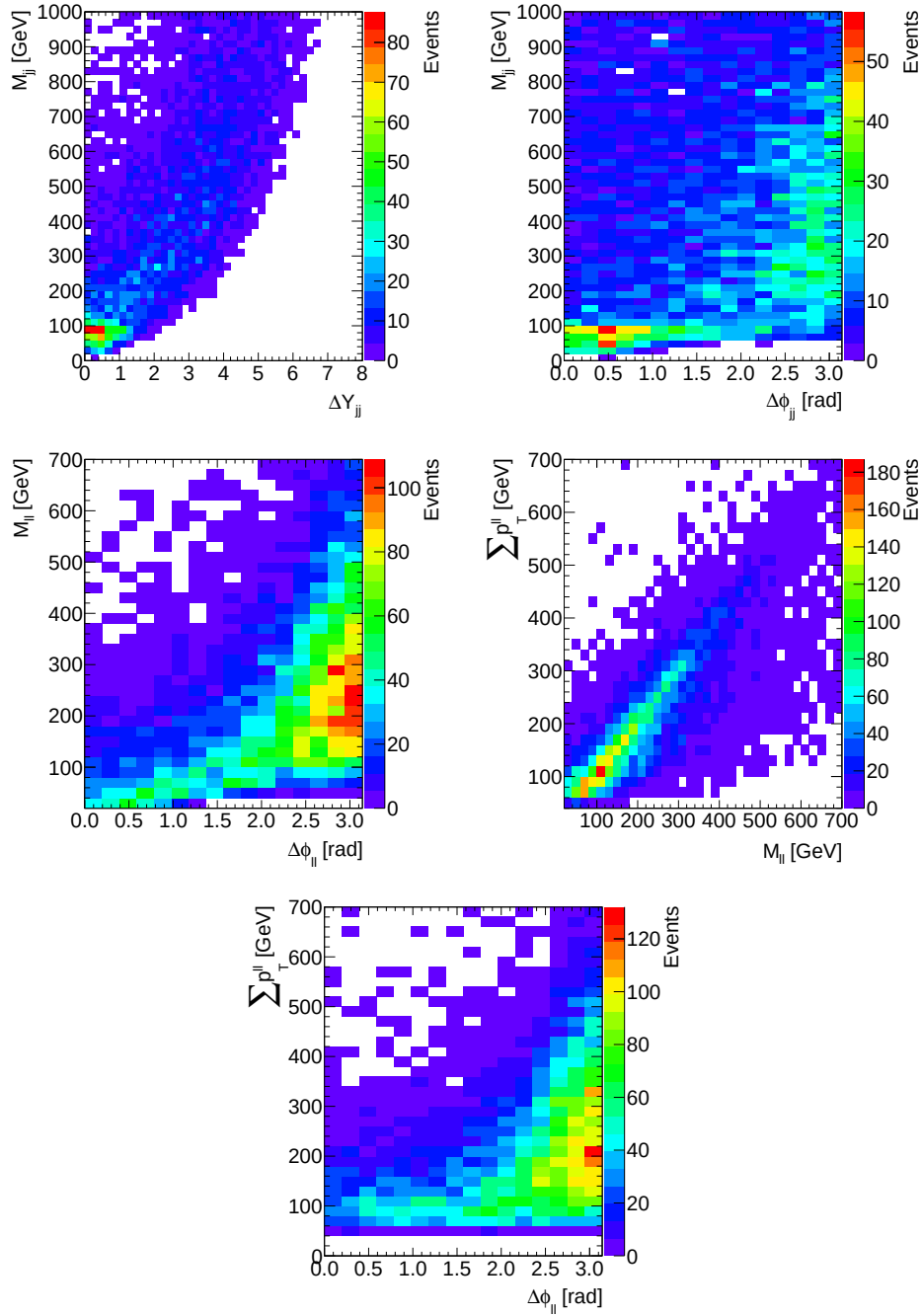


Figure 7.9: Two dimensional distributions of combinations of the introduced kinematic variables that show correlations. The diagrams were produced for the aQGC point $\alpha_4 = \alpha_5 = 0.1$ and after the $N_{\text{jets}} \geq 2$ cut.

Hence, our variables of interest in the context of an optimization of the aQGC measurement are:

$$\Delta\phi_{ll}, \quad \sum p_T^{ll}, \quad \Delta Y_{jj} \quad \text{and} \quad M_{jj}.$$

7.8 Statistical Analysis

Given a measured number of events, statistical methods can be used to evaluate the agreement of a model with the observed data and to set constraints on its parameters.

There are two fundamental approaches to define probabilities. The frequentist approach addresses the probability of the outcome of an experiment for a given theory $P(\text{experiment} | \text{theory})$, while the Bayesian approach tries to find the "degree of belief" in a certain theory, given the experimental measurements $P(\text{theory} | \text{experiment})$, requiring an "a priori" probability for the theory or its parameters. Since we want to avoid the dependence on such priors, the frequentist approach will be applied throughout this work.

The profile Likelihood method is used to derive constraints on the aQGC parameters α_4 and α_5 . This method will be explained in the following and the Likelihood function as it was used for the aQGC measurement will be introduced.

7.8.1 Profile Likelihood Method

The profile Likelihood function provides the possibility to account for uncertainties in a measurement that are not of statistical nature. Therefore, additional parameters, so called *nuisance parameters*, are introduced. However, their values are not of interest. If $L(\mu, \vec{v})$ is the Likelihood function with the parameter of interest μ and a set of nuisance parameters $\vec{v}$, the profile Likelihood has the form:

$$L_p(\mu) = L(\mu, \hat{\vec{v}}(\mu)), \quad (7.17)$$

with $\hat{\vec{v}}(\mu)$ being the best estimate for a given value μ . With this Likelihood function, test statistics are defined which are functions t that map all possible observations to a real number: $t(\mathbf{x} = y \in R)$. In many cases they include a ratio of the profiled and the unprofiled Likelihood function [66].

Several methods that set constraints on parameters of interest use test statistics, for example the CL_s method [67] or the Cousins and Feldman construction [68]. As a first approach to set constraints on aQGC in VBS for the first time we chose the *Delta Log Likelihood Method*.

Delta Log Likelihood Method

Suppose we have a random variable x that follows a Gaussian distribution which is a good approximation for most use cases. The probability of the measured value x lying within $[\mu - \delta; \mu + \delta]$, with μ being the true value, is then given by:

$$1 - \alpha = \frac{1}{\sqrt{2\pi}\sigma} \int_{\mu-\delta}^{\mu+\delta} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \quad (7.18)$$

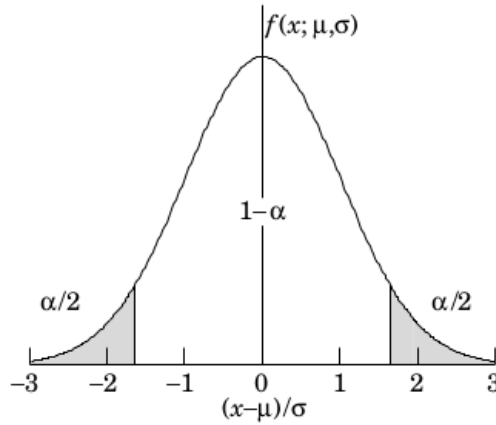


Figure 7.10: Illustration of a 90% symmetric confidence interval (unshaded) for one parameter of interest and Gaussian distributed nuisance parameters. (Picture taken from [6])

CL [%]	C
68.27	0.50
90	1.35
95	1.92
99	3.32

Table 7.6: List of some confidence levels and the corresponding lower bound on t_μ for a $\chi^2 = (\delta/\sigma)^2$ function with one degree of freedom.

This interval is called *confidence interval* (CI) at the *confidence level* (CL) $1 - \alpha$. Figure 7.10 shows a confidence interval with a confidence level of 90%.

A test statistic can be defined by

$$t_\mu = -\ln \frac{L(\mu, \hat{\vec{v}}(\mu))}{L(\hat{\mu}, \hat{\vec{v}})} = \Delta \ln L, \quad (7.19)$$

with $L(\hat{\mu}, \hat{\vec{v}})$ being the value of the Likelihood function for the best estimates of μ and $\vec{v}$ and hence, the minimum of the profile $L(\mu, \hat{\vec{v}}(\mu))$. t_μ follows a χ^2 distribution with one degree of freedom.

Values of μ with $t_\mu \geq C$ can be excluded at some confidence level with C being a constant depending on the CL and the number of degrees of freedom.

Some examples of confidence levels and their corresponding value of C are shown in Table 7.6.

7.8.2 The Likelihood Function

The number of events that are left after the selection is Poisson distributed since the probability of passing all requirements is small compared to the huge amount of events that are detected. Therefore, the Likelihood function includes a Poissonian with the expected event

yield N_{exp} being the mean value and the number of measured events N the random variable. The number of expected events is the sum of all selected signal and background events, $N_{\text{exp}} = S + B$. The estimation of the number of background events is accompanied by systematic uncertainties as described in Section 7.4. Therefore, the estimated number of background events B_0 is Gaussian distributed around the true value B . The standard deviation $\sigma = \Delta B_0$ takes into account the evaluated relative systematic uncertainty. The Likelihood function is then given by:

$$L(\mu, \Delta B_0) = \text{Poi}(N|\mu S + B) \times G(B_0, B, \Delta B_0) \quad (7.20)$$

$$= \frac{(\mu S + B)^N}{N!} e^{-(\mu S + B)} \cdot \frac{1}{\Delta B_0 \sqrt{2\pi}} e^{-\frac{(B_0 - B)^2}{2(\Delta B_0)^2}} \quad (7.21)$$

with μ being a scaling factor of the number of signal events. It is the parameter of interest of this measurement since it indicates which multiple of the number of signal events is compatible with the observed data. In general, there are several sources for background and systematic uncertainties v_j . Therefore, the Likelihood takes the form:

$$L(\mu, \vec{v}) = \text{Poi}(N|\mu S(\vec{v}) + \sum_i B_i(\vec{v})) \times \prod_j G(v_{0,j}, v_j, 1) \quad (7.22)$$

with i indicating the background source. This takes into account the correlations between the effects of one systematic on the yields of different background sources.

$B_i(\vec{v})$ can be parametrized by

$$B_i(\vec{v}) = B_{0,i} (1 + \sum_j v_j \Delta_{ij}), \quad \text{with} \quad B_i(\vec{v}_0) = B_{0,i} \quad (7.23)$$

and with Δ_{ij} being the relative uncertainty of background i due to the systematic j . The Likelihood function is then given by:

$$L(\mu, \vec{v}) = \prod_{c \in \{\text{ee}, \text{em}, \text{mm}\}} \text{Poi}(N_c|\mu S_c + \sum_{ij} (1 + v_j \Delta_{ij}) B_{0,i,c}) \times \prod_j G(v_{0,j}, v_j, 1), \quad (7.24)$$

where the index c is added to account for the treatment of each final state (channel).

This Likelihood function is used in the measurement of the aQGC parameters.

7.9 Measurement of aQGC

As mentioned in Section 7.5, the Delta Log Likelihood Method presented in the previous section is used to set upper constraints on the $W^\pm W^\pm \text{jj}$ EW cross section which can be translated to constraints in the aQGC parameters α_4 and α_5 by applying the exclusion condition from Equation 7.15.

7.9.1 Procedure

The number of signal events S in the Likelihood (7.24) is always set to the number of events of the $W^\pm W^\pm jj$ EW SM process in the fiducial phase space. Hence, μ_{UL} quantifies how much the SM cross section could be increased to be still compatible within a certain CL with the data:

$$\sigma_{fid}^{UL} = \mu_{UL} \cdot \sigma_{fid}^{SM} \quad (7.25)$$

The limit of μ for a 95% CL is determined by using the test statistic from Equation 7.19:

$$t_{\mu_{UL}} = 1.92. \quad (7.26)$$

Assuming that the Standard Model process of $W^\pm W^\pm jj$ EW exists, μ can never be smaller than 1 since the signal cross section increases for increasing aQGC parameters as shown in Section 7.6.2. Only at very small coupling strengths ($\alpha_i \sim 0.05$), a destructive interference of about 2% is expected (see Section 2.3.3) which is neglected.

If the best estimate of the parameter of interest $\hat{\mu}$ is smaller than one due to downwards fluctuations of the data, t_μ will be changed to

$$t_\mu = -\ln \frac{L(\mu, \hat{\hat{v}}(\mu))}{L(1, \hat{\hat{v}})}. \quad (7.27)$$

This leads to a confidence interval whose coverage is larger than the envisaged 95% and is hence conservative. The constraint that the region $\mu < 1$ is regarded as unphysical, leads to the effect that either one sided or two sided intervals can be observed. If the lower value of μ for which Equation 7.26 is fulfilled, is larger than one, a two sided confidence interval with the lower bound μ_{LL} is obtained.

Fitting the Likelihood function to the Asimov data set¹³ which assumes the observation to be in exact agreement with the SM prediction, $\hat{\mu} = 1$ is always true. The corresponding limits are called *expected limits* and are always upper limits.

For finding the limits in α_4 and α_5 that correspond to the upper limit, the α_4 - α_5 -plane has been scanned, searching the point which is closest to the exclusion border defined by Equation 7.15. The scan was conducted for $\alpha_4 \in (0, 0.2)$ and $\alpha_5 \in (0, 0.2)$ with a step width of 0.01. The cross section was initially evaluated for a step width of 0.02 and the acceptances and efficiencies only for the points where the WHIZARD samples have been produced. Therefore, these values are interpolated bilinearly between their corresponding grid points.

7.9.2 Results

Table 7.7 lists the observed and expected events for a SM signal in the fiducial phase space, the μ_{UL} for a 95% CL and the corresponding one dimensional constraints on α_4 and α_5 in the first quadrant.

In Figure 7.11 the test statistic t_μ for the expected and observed number of events is shown. The minimum of the expected curve is shifted to $\mu = 1.6$ due to the upwards fluctuation of the data. Hence, the observed limits are less tight than the expected ones and for the 68%

¹³The term Asimov data set is used for the most representative data set of a hypothesis.

CL even a two sided interval is present. The 2D contours are shown in Figure 7.12 for a 68%, 95% and 99% CL. They follow the contours of the fiducial cross section in the α_4 - α_5 -plane. The counting experiment we are doing contains only one degree of freedom: the cross section, which can be parametrised with as many parameters as we want. Therefore, the one dimensional constraints are always the interceptions of the two dimensional constraints with the axes.

These are the first constraints that have ever been set on anomalous couplings in the quartic vertex of vector boson scattering.

	N	$\mu_{\text{UL}} \text{ (95\% CL)}$	α_4^{UL}	α_5^{UL}
expected	26.08	2.19	0.09	0.16
observed	32	2.94	0.14	0.21

Table 7.7: Summary of number of expected and observed events N and the corresponding 1D constraints on α_4 and α_5 in the first quadrant.

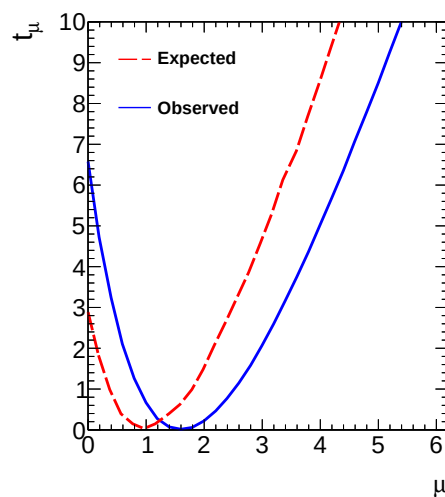


Figure 7.11: Test statistic in dependence of the signal strength μ .

7.10 Cut optimization

In this section, the influence of cuts on aQGC sensitive variables shall be studied. Following the discussion in Section 7.7, $\Delta\phi_{ll}$, $\sum p_T^{ll}$, and ΔY_{jj} have been proven to be very aQGC sensitive and have a good discrimination between the signal and the background. M_{jj} is not sensitive to aQGC but since it has good capabilities to discriminate between the signal and the background as well it is also considered in the optimization.

In the following, the cut value ε of one of these variables of interest x will be defined by:

$$x = \varepsilon \quad (7.28)$$

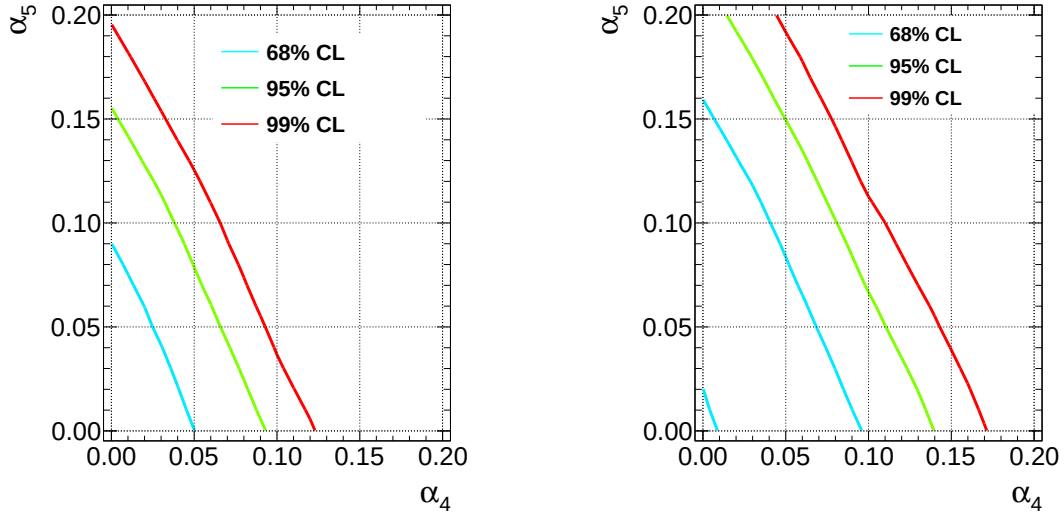


Figure 7.12: Contours of expected (left) and observed (right) constraints in the first quadrant of the α_4 - α_5 -plane. The blue line denotes the 68%, the green line the 95% and the red line the 99% confidence level contour.

All events with smaller values of x than its cut value ε will be discarded. For example, the notation $M_{jj} = 500$ GeV means that all events with $M_{jj} < 500$ GeV will be discarded. For M_{jj} , cut values smaller than 200 GeV will not be investigated in order to ensure that the peak at $\sim M_W - M_Z$ coming from triboson production is not in the signal region (see Section 7.7).

7.10.1 Optimization Setup

In the optimization procedure different cut sets were tested for the resulting upper limits in α_4 and α_5 . For technical reasons, only one-, two- or three-dimensional optimizations are possible. For each cut set, the following steps were executed:

1. The acceptances and efficiencies are calculated for each aQGC WHIZARD sample since the fiducial phase space changes with each cut set.
2. The signal and background yields after all cuts are evaluated and the Likelihood function is constructed. Since the evaluation of the systematic uncertainties for each cut set would increase the computing time immensely, the uncertainties were set to the values evaluated for the fiducial phase space: $M_{jj} = 500$ GeV, $\Delta Y_{jj} = 2.4$, $\Delta \phi_{1l} = 0$ and $\Sigma p_T^{ll} = 0$.
3. The profile Likelihood function is evaluated in fitting the Likelihood to the Asimov data set and hence, determining the nuisance parameters for each value of μ . μ_{UL} is calculated using the Delta Log Likelihood Method.
4. The upper limit cross section $\sigma_{UL} = \mu_{UL} \cdot \sigma_{SM}$ is converted into one dimensional constraints in α_4 and α_5 by applying Equation 7.15.

7.10.2 Results

In the following, the influence of cuts in $\Delta\phi_{ll}$, $\sum p_T^{ll}$, ΔY_{jj} , and M_{jj} on the aQGC constraints is presented. An optimal cut set of $\Delta\phi_{ll}$ and $\sum p_T^{ll}$ will be investigated for the nominal selection in M_{jj} and ΔY_{jj} . Additionally, optimal cut sets in $\Delta\phi_{ll}$, $\sum p_T^{ll}$, and ΔY_{jj} will be searched for a constant cut in M_{jj} . If not stated otherwise the shown results are expected limits.

Influence of Cuts on M_{jj} , ΔY_{jj} , $\sum p_T^{ll}$, and $\Delta\phi_{ll}$

The cuts in $\Delta\phi_{ll}$, $\sum p_T^{ll}$, ΔY_{jj} , and M_{jj} can take the following cut values:

$$\begin{aligned} M_{jj} &\in \{200, 300, 400, 500, 600\} \text{ GeV} \\ \Delta Y_{jj} &\in \{0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0\} \\ \Delta\phi_{ll} &\in \{0.00, 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 2.75\} \\ \sum p_T^{ll} &\in \{0, 50, 100, 150, 200, 250, 300\} \text{ GeV} \end{aligned}$$

Figure 7.13 illustrates the dependence of α_4^{UL} and α_5^{UL} on cuts in M_{jj} and ΔY_{jj} , M_{jj} and $\sum p_T^{ll}$, and M_{jj} and $\Delta\phi_{ll}$. The cut value is always the bin center. There are no cuts applied on the other two variables.

By applying only a M_{jj} cut, the upper limit in α_4 and α_5 decreases by 0.04 which corresponds to $\sim 30\%$ and $\sim 20\%$ improvement respectively. A cut on ΔY_{jj} improves the upper limits by 0.05 which corresponds to $\sim 35\%$ in α_4 and $\sim 25\%$ in α_5 , a cut on $\sum p_T^{ll}$ leads to a decrease of even 0.07 which corresponds to $\sim 50\%$ in α_4 and to $\sim 35\%$ in α_5 and a cut in $\Delta\phi_{ll}$ to a decrease of 0.04 (28%) in α_4 and 0.03 (15%) in α_5 .

The relative decrease of the limits for the different cuts shows that ΔY_{jj} and $\sum p_T^{ll}$ have a significantly higher influence on the limits than the M_{jj} and $\Delta\phi_{ll}$ cuts. For each cut on M_{jj} , the same optimal limits can be achieved by applying a cut on ΔY_{jj} and $\sum p_T^{ll}$. Higher M_{jj} cut values reduce the cut values of ΔY_{jj} and $\sum p_T^{ll}$ for which the lowest upper limit is reached.

The cut value of M_{jj} is not of importance when applying a cut on ΔY_{jj} or $\sum p_T^{ll}$ since the minimum can be (almost) reached by those cuts alone. Therefore, the M_{jj} requirement is set to a constant value in the following, when optimizing the other cut variables.

Two dimensional Optimization in $\Delta\phi_{ll}$ and $\sum p_T^{ll}$ for the Nominal Cuts in ΔY_{jj} and M_{jj}

In general, sticking to the nominal cut values has the advantage that the background estimations and evaluation of systematic uncertainties was already done for this fiducial region.

Figure 7.14 shows the $\Delta\phi_{ll}$ and $\sum p_T^{ll}$ distributions of the expected total number of events for a SM signal (filled) and for two different aQGC cases where one parameter is set to 0.1 and the other to zero. The distributions were made after the nominal selection. For comparison, the observed data is plotted in black dots with its statistical uncertainty.

Especially from the $\Delta\phi_{ll}$ distribution it can be deduced that the observed number of events is larger than the expected number. This discrepancy is compatible with the presence of aQGC.

In order to achieve a higher sensitivity to aQGC, the nominal selection is expanded by a $\Delta\phi_{ll}$ and a $\sum p_T^{ll}$ cut for which the optimal cut values are searched. Therefore, for every combina-

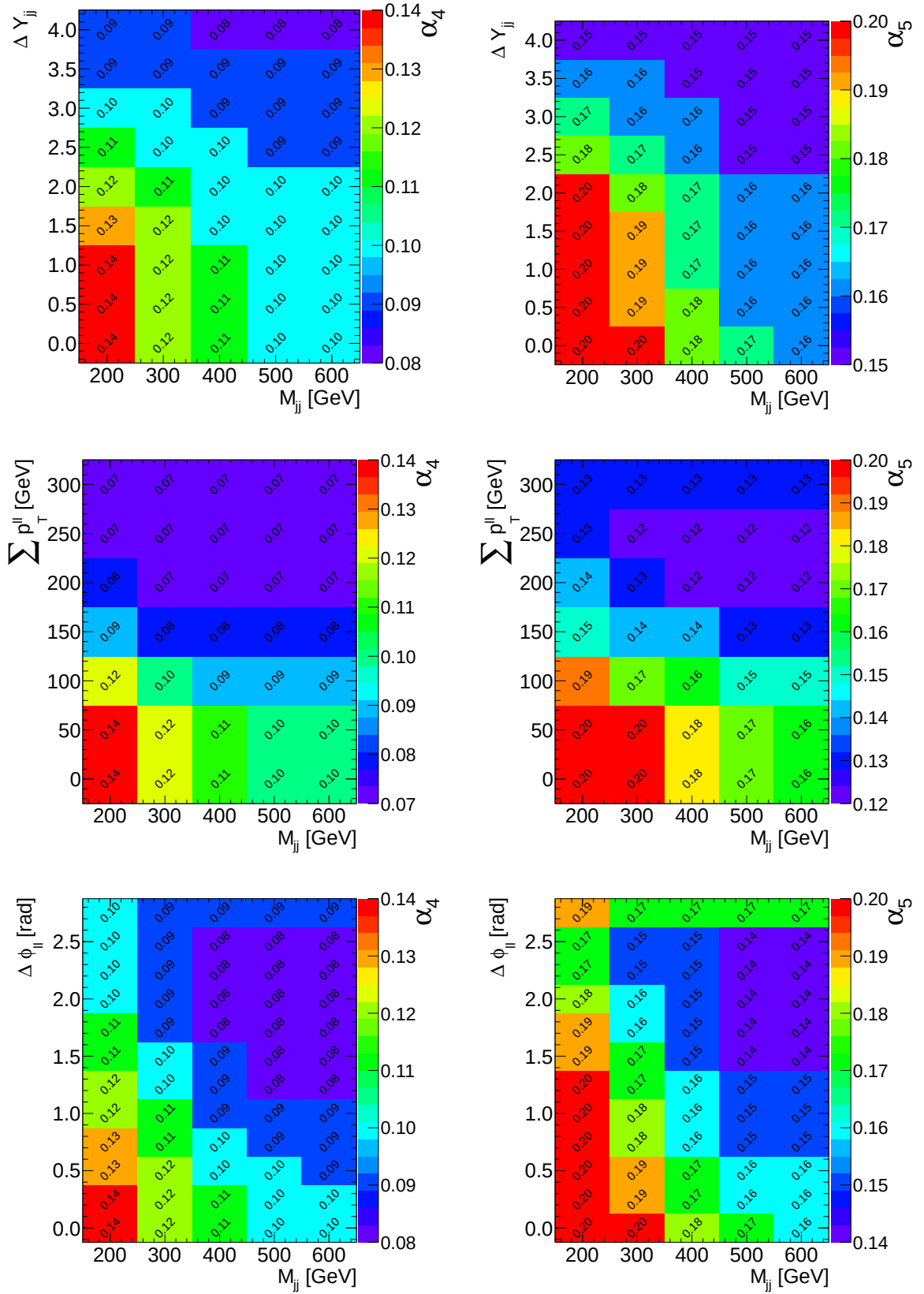


Figure 7.13: Dependence of α_4^{UL} (left column) and α_5^{UL} (right column) on cuts in M_{jj} and ΔY_{jj} (upper row), M_{jj} and $\sum p_T^{\text{ll}}$ (middle row), and M_{jj} and $\Delta \phi_{\text{ll}}$ (lower row). The cut values of the other variables are set to zero.

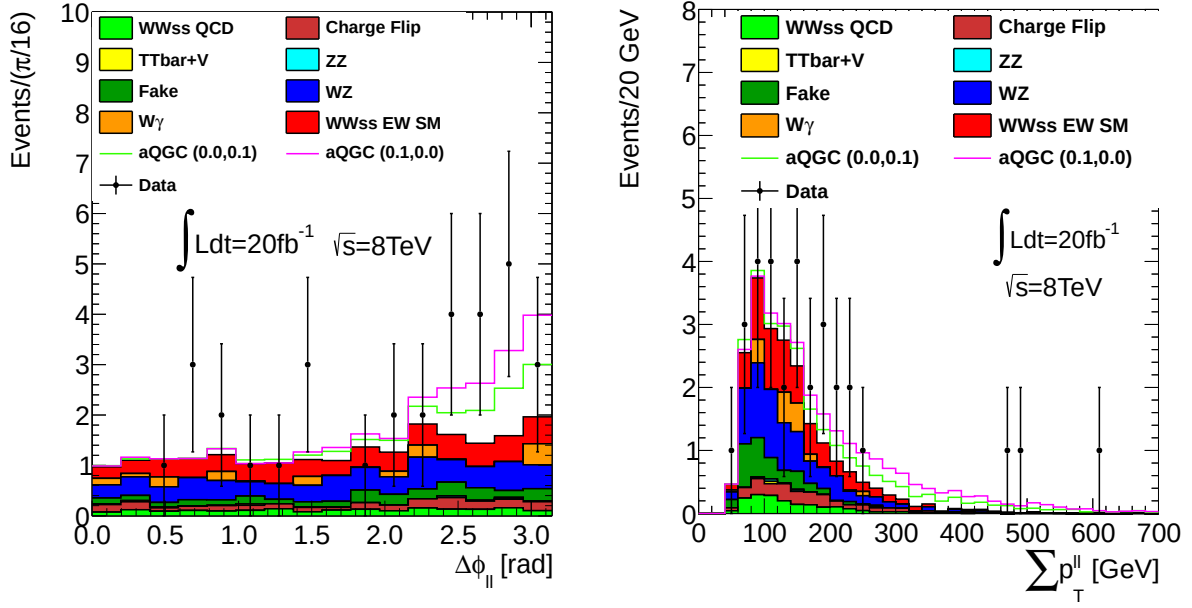


Figure 7.14: Distribution of the expected number of events in the SM case (filled), and in the presence of aQGC of the strengths $\alpha_4 = 0.1$, $\alpha_5 = 0$ (magenta line) and $\alpha_4 = 0$, $\alpha_5 = 0.1$ (green line) over $\Delta\phi_{||}$ (left) and $\sum p_T^{||}$ (right). The fiducial phase space cuts from Section 7.2.2 were applied. The data points with their statistical uncertainties are given as well.

tion of

$$\Delta\phi_{||} \in \{0.00, 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 2.75\} \quad \text{and} \\ \sum p_T^{||} \in \{0, 50, 100, 150, 200, 250, 300\} \text{ GeV}$$

the one dimensional upper constraints on the aQGC parameters are evaluated.

Figure 7.15 illustrates the dependence of the upper limit in α_4 and α_5 on cuts in $\Delta\phi_{||}$ and $\sum p_T^{||}$. It shows that the lowest upper limits in α_4 and α_5 (0.05 and 0.10) can be achieved for several cut sets. Again, the large effect of the $\sum p_T^{||}$ cut is obvious since it improves the limit already by 0.03 in α_4 and 0.05 in α_5 on its own. An additional cut in $\Delta\phi_{||}$ leads only to an improvement of 0.01 in both of the aQGC parameters.

Table 7.8 shows all cut sets that resulted in the smallest α_4^{UL} and α_5^{UL} . The table is sorted descending in the number of signal events S^{14} .

For the cut set with the highest event yields ($\Delta\phi_{||} = 1.75$, $\sum p_T^{||} = 200$ GeV) 3 events are expected in total. This corresponds to uncertainties due to the MC statistics of 9% for the background and 6% for the signal. In general, cut sets are preferred where the statistics is still reasonably high. In the Likelihood function, the statistical uncertainties are included as nuisance parameters and hence, are taken into account in the evaluation of the limits. However, in other studies like the evaluation of systematic uncertainties, events in the fiducial region are counted. If the statistics is low, this number can fluctuate strongly.

¹⁴The reader shall be reminded that the signal is defined as the $W^\pm W^\pm jj$ EW SM contribution

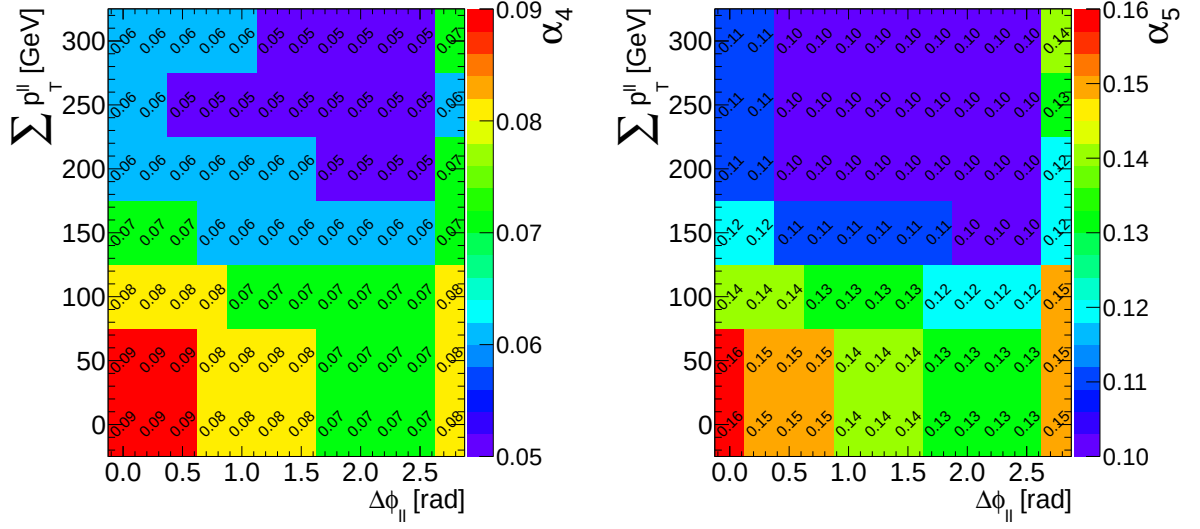


Figure 7.15: Illustration of upper limits in α_4 (left) and α_5 (right) in dependence of the $\Delta\phi_{||}$ and the $\sum p_T^||$ cut value when the cuts in ΔY_{jj} and M_{jj} are set to their nominal values.

$\Delta\phi_{ }$	$\sum p_T^ $ [GeV]	B	S	μ^{UL} (CL 95%)	α_4^{UL}	α_5^{UL}
1.75	200	1.32	1.71	3.91	0.05	0.1
2	200	1.19	1.52	4.14	0.05	0.1
2.25	200	1.02	1.27	4.54	0.05	0.1
0.5	250	0.99	1.23	4.62	0.05	0.1
0.75	250	0.95	1.17	4.74	0.05	0.1
1	250	0.90	1.10	4.92	0.05	0.1
1.25	250	0.87	1.04	5.06	0.05	0.1
1.5	250	0.76	0.99	5.12	0.05	0.1
2.5	200	0.75	0.95	5.30	0.05	0.1
1.75	250	0.70	0.91	5.36	0.05	0.1
2	250	0.65	0.84	5.63	0.05	0.1
2.25	250	0.52	0.70	6.22	0.05	0.1
1.25	300	0.41	0.59	6.89	0.05	0.1
1.5	300	0.35	0.58	6.81	0.05	0.1
2.5	250	0.36	0.53	7.30	0.05	0.1
1.75	300	0.31	0.53	7.18	0.05	0.1
2	300	0.29	0.50	7.49	0.05	0.1
2.25	300	0.25	0.42	8.38	0.05	0.1
2.5	300	0.16	0.34	9.37	0.05	0.1

Table 7.8: Cut sets of $\Delta\phi_{||}$ and $\sum p_T^||$ that resulted in the best constraints in α_4 and α_5 with ΔY_{jj} and M_{jj} being at its nominal values $\Delta Y_{jj} = 2.4$ and $M_{jj} = 500$ GeV. The corresponding values for μ_{UL} and the signal and background yields S and B are listed as well.

	$\frac{A_{(0.0,0.1)}}{A_{\text{SM}}}$	$\frac{A_{(0.1,0.0)}}{A_{\text{SM}}}$	$\frac{\varepsilon_{(0.0,0.1)}}{\varepsilon_{\text{SM}}}$	$\frac{\varepsilon_{(0.1,0.0)}}{\varepsilon_{\text{SM}}}$
nominal selection	1.1	1.2	1.07	1.13
nominal selection + $\Delta\phi_{\parallel} = 1.75 + \sum p_T^{\parallel} = 200$ GeV	2.8	4.0	1.04	1.07

Table 7.9: Comparison of the acceptance and efficiency ratios between the aQGC points (α_4, α_5) and the SM case for different cut sets.

The cut set shown in the last row of Table 7.8 constrains the phase space very tightly. A signal yield of 0.34 and a background yield of 0.16 correspond to statistical uncertainties of 13% and 24% respectively. For the background, it is of the order of the systematic uncertainties. The fact, that the limits are minimal though μ_{UL} increases for tighter cuts shows the high discrimination power of the cut variables.

A large μ_{UL} means that the product of the acceptance and efficiency ratios between the aQGC point and the SM case is large (see Equation 7.15). Table 7.9 shows these ratios for the aQGC points (0.0,0.1) and (0.1,0.0) for the nominal selection and the nominal selection with additional cuts on $\Delta\phi_{\parallel}$ and $\sum p_T^{\parallel}$. The acceptance ratios are significantly higher for the optimized selection than for the nominal selection. The efficiency ratios are roughly the same. We can conclude that optimizing the sensitivity to aQGC constraints means optimizing the ratio between the acceptances of the aQGC samples and the SM sample.

Additionally a MC background statistics enhanced by a factor of 6 would bring the statistical uncertainties of the background for tight cut sets back into the range of 10%. This would increase the sensitivity to aQGC since harder cuts can be applied and therefore the kinematic features of aQGC can be exploited. However, in these kinematic regions systematic uncertainties, especially those who are estimated from data driven methods, become larger due to the lack of statistics in data.

Three Dimensional Optimization of ΔY_{jj} , $\Delta\phi_{\parallel}$ and $\sum p_T^{\parallel}$

In order to find optimal cuts in $\sum p_T^{\parallel}$, $\Delta\phi_{\parallel}$ and ΔY_{jj} , α_4^{UL} and α_5^{UL} are calculated for every combination of

$$\begin{aligned} \Delta Y_{jj} &\in \{0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0\} \\ \Delta\phi_{\parallel} &\in \{0.00, 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 2.75\} \quad \text{and} \\ \sum p_T^{\parallel} &\in \{0, 50, 100, 150, 200, 250, 300\} \text{ GeV.} \end{aligned}$$

Since the M_{jj} cut was proven to have only a small influence on the limits it is first set to its nominal value ($M_{jj} = 500$ GeV) and then to 300 GeV for comparison.

Table 7.10 shows the cut sets which resulted in the best constraints. For $M_{jj} = 300$ GeV, the limits are smaller by $\sim 10\%$ due to the significantly increased acceptance ratios between the aQGC samples and the SM sample. These are achieved by the harder cuts in $\sum p_T^{\parallel}$ and $\Delta\phi_{\parallel}$ which are only possible for $M_{jj} = 300$ GeV. The looser M_{jj} cut increases the statistics and hence, the statistical uncertainties at the end of the selection are still of acceptable size such that μ_{UL} does not compensate the increase of the acceptance and efficiency ratios.

M_{jj}	ΔY_{jj}	$\Delta\phi_{ll}$	$\sum p_T^{ll}$	B	S	$\mu_{UL}^{CI\ 95\%}$	α_4^{UL}	α_5^{UL}
500	3.0	2.00	150	1.93 ± 0.20 (10.4%)	2.03 ± 0.11 (5.4%)	3.69	0.05	0.10
300	3.0	2.25	250	0.73 ± 0.09 (12.8%)	0.66 ± 0.06 (9.5%)	6.79	0.04	0.09
M_{jj}	ΔY_{jj}	$\Delta\phi_{ll}$	$\sum p_T^{ll}$	$\frac{A_{(0.0,0.1)}}{A_{SM}}$	$\frac{A_{(0.1,0.0)}}{A_{SM}}$	$\frac{\varepsilon_{(0.0,0.1)}}{\varepsilon_{SM}}$	$\frac{\varepsilon_{(0.1,0.0)}}{\varepsilon_{SM}}$	
500	3.0	2.00	150	2.4	3.4	1.11	1.14	
300	3.0	2.25	250	5.20	8.06	1.01	1.05	

Table 7.10: Cut sets of ΔY_{jj} , $\Delta\phi_{ll}$, and $\sum p_T^{ll}$ [GeV] for a constant cut in M_{jj} [GeV] that resulted in the best constraints on α_4 and α_5 with corresponding variables. The uncertainties of the signal yields S and background yields B are the statistical uncertainties from the MC statistics. In round brackets the relative statistical uncertainties are given.

Observed Limits of the Optimal Cut Set

The optimal cut set was found in the previous paragraph and is defined by:

$$\begin{aligned}
 M_{jj} &= 300 \text{ GeV}, \\
 \Delta Y_{jj} &= 3.0, \\
 \Delta\phi_{ll} &= 2.25, \quad \text{and} \\
 \sum p_T^{ll} &= 250 \text{ GeV}.
 \end{aligned} \tag{7.29}$$

The number of observed events for this region is zero which results in upper constraints of

$$\begin{aligned}
 \alpha_4^{UL} &= 0.02 \quad \text{and} \\
 \alpha_5^{UL} &= 0.04.
 \end{aligned} \tag{7.30}$$

They are tighter than the expected limits due to the downwards fluctuation of the data in this region. For this cut set Equation 7.27 has to be applied since the minimum of the test statistic over μ lies at $\hat{\mu} < 1$. Hence, the observed limits are conservative.

Figure 7.16 shows distributions of ΔY_{jj} , $\Delta\phi_{ll}$, and $\sum p_T^{ll}$ for $M_{jj} = 300$ GeV when no cut on the plotted variable is applied but the cuts on the other two variables are set to the values given in Equation 7.29.

One can see that in all distributions the expected number of events in the presence of aQGC is significantly higher than the number of expected events in the SM case. The data is in good agreement with the SM prediction in the $\Delta\phi_{ll}$ distribution (1,79 events predicted, 2 observed) and the ΔY_{jj} distribution (3,09 events predicted, 3 observed). However, in the $\sum p_T^{ll}$ distribution the data fluctuates upwards. In total 10,58 events are predicted by the SM and 15 events are observed. Nevertheless this is still within the statistical uncertainties.

In all distributions no observed events are present in the regions where the distributions including aQGC become large in comparison to the SM prediction. This is why the observed limits are tighter than the expected limits in the optimized phase space.

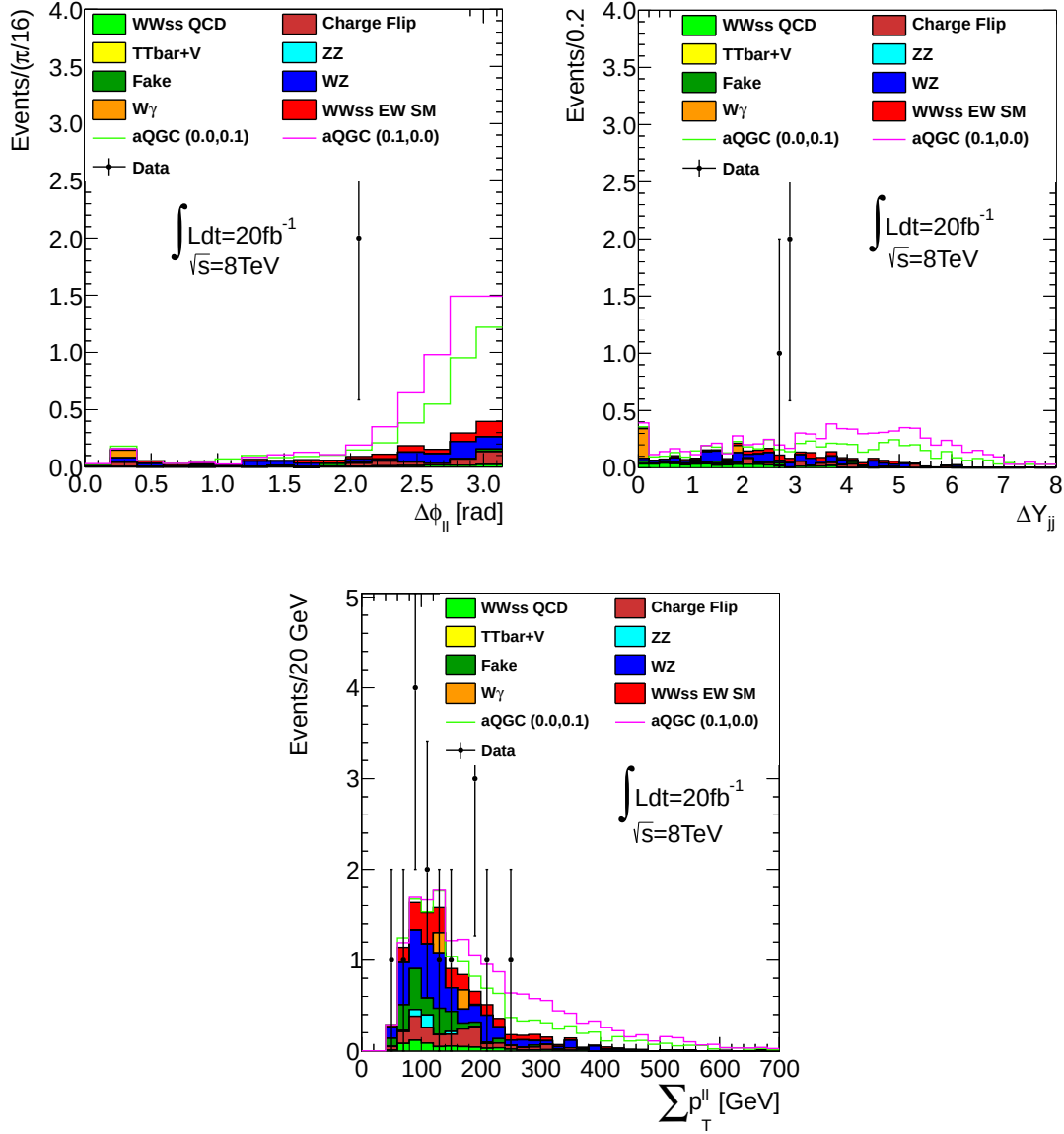


Figure 7.16: Distributions of ΔY_{jj} , $\Delta\phi_{||}$, and $\sum p_T^||$ for the optimal cut set of Equation 7.29 when no cut on the respective plotted variable is applied.

7.11 Discussion and Conclusions

The $W^\pm W^\pm jj$ EW process has been measured for the first time with a significance of 3.4σ by [59].

Using these results constraints on the aQGC parameters α_4 and α_5 were evaluated in this . Here, several assumptions have been adopted which shall be summarized:

- The interference between $W^\pm W^\pm jj$ QCD and EW production and its dependence on aQGC has been neglected.
- The k -factor that scales the LO fiducial cross section to its NLO value was assumed to be not aQGC dependent and has been the same for each aQGC point ($k = 1.32$).
- The systematic uncertainties were evaluated only in the fiducial phase space and have been the same for each cut set. Since they are cut dependent, they would have to be re-evaluated for each cut set which was not possible due to limited computing time.
- The factorization scale of the samples is not the same as for the cross sections in the extended phase space that were generated in a finer grid in the first quadrant of the α_4 - α_5 -plane. The differences in the results due to the different scales have been neglected.
- The influence of aQGC in the WZ background has not yet been studied and therefore, has been neglected.
- A linear interpolation between the evaluated cross sections, acceptances, and efficiencies has been done with a step width of 0.01 which limits the precision of the constraints to this value.

In this work, only positive aQGC parameters have been studied since only for those fully simulated samples were available. In order to set two dimensional limits in the full α_4 - α_5 -plane, more samples would need to be generated in order to calculate the acceptances and efficiencies.

Furthermore, a first optimization of the aQGC measurement has been done. The influence of cuts on the variables M_{jj} , $\Delta\phi_{ll}$, $\sum p_T^{ll}$, and ΔY_{jj} has been studied and a $\sum p_T^{ll}$ cut was found to have the highest influence with about $\sim 50\%$ in α_4 and $\sim 35\%$ in α_5 .

Considering the optimization of the nominal selection in adding cuts in $\sum p_T^{ll}$ and $\Delta\phi_{ll}$ a cut on $\sum p_T^{ll}$ at 200 GeV would suffice to improve the aQGC constraints significantly. An additional cut on $\Delta\phi_{ll}$ at 1.75 leads to a decrease of the limits by 10% in α_4 and 16% in α_5 .

An optimization of the cuts in $\Delta\phi_{ll}$, $\sum p_T^{ll}$ and ΔY_{jj} for $M_{jj} = 300$ GeV has shown that an optimal cut set (defined in Equation 7.29) can be found. The expected upper limits are improved by 50% in α_4 and 44% in α_5 compared to the nominal selection. Table 7.11 summarizes the results for the nominal and the optimal selection.

The high improvement in the observed constraints is explained by the upwards fluctuation of the data in the fiducial phase space and its downwards fluctuation in the phase space defined by the optimal cut set.

	expected		observed	
	α_4^{UL}	α_5^{UL}	α_4^{UL}	α_5^{UL}
nominal selection	0.09	0.16	0.14	0.20
optimal cut set	0.04	0.09	0.02	0.04

Table 7.11: Comparison of the expected and observed upper limits evaluated for the nominal selection and the optimal cut set.

Chapter 8

Conclusion

In this thesis, the analysis of the scattering of two equally charged W bosons in the dileptonic final state was presented with the focus on constraining the parameter space of the anomalous coupling parameters α_4 and α_5 . They parametrize high energy effects of new physics and contribute to the coupling in the four vector boson vertex.

For the first time, the scattering of two massive bosons with the focus on the quartic vertex was measured [59]. This has been done with the data recorded in 2012 by the ATLAS detector at a center of mass energy of $\sqrt{s} = 8$ TeV and an integrated luminosity of $\int L dt = 20 \text{ fb}^{-1}$.

The scattering of two equally charged W bosons has been observed for the first time with a significance of 3.4σ and its cross section was extracted with the result

$$\sigma_{\text{fid,obs}}^{W^\pm W^\pm \text{jj EW}} = 1.410 \pm_{0.466}^{0.555} \text{ fb},$$

A one sided 95% CL interval of cross sections was determined which was translated into one and two dimensional intervals in the α_4 - α_5 -plane. The observed one dimensional upper limits are

$$\alpha_4 \leq 0.14 \quad \text{and} \quad \alpha_5 \leq 0.21 \quad \text{at 95\% CL.}$$

With the rule of thumb [29]

$$\Lambda \gtrsim \frac{v}{\sqrt{\alpha}} \quad (8.1)$$

a lower bound of the scale of new physics Λ can be determined from the measured limits. It lies in the range

$$\Lambda \gtrsim 600 \text{ GeV.}$$

From various dilepton and dijet variables, four variables were selected on which requirements were set and optimized by searching for cut sets for which the expected one dimensional upper limits become small.

The main result is that the sensitivity of the search for anomalous couplings can be improved by imposing requirements on aQGC sensitive variables. Such variables are the scalar sum of the lepton transverse momenta $\sum p_T^\text{ll}$, the difference in the lepton polar angles $\Delta\phi_\text{ll}$, and the difference in the jet rapidities ΔY_jj . Especially a cut on $\sum p_T^\text{ll}$ shows a high improvement of 50% in α_4 and 35% in α_5 constraints.

An optimal cut set was found for which upper limits of

$$\alpha_4 \leq 0.04 \quad \text{and} \quad \alpha_5 \leq 0.09 \quad \text{at 95\% CL}$$

are expected. This corresponds to an improvement of 70% in α_4 and 55% in α_5 compared to the expected upper limits evaluated with the nominal selection. The lower bound for the scale of new physics improves to

$$\Lambda \gtrsim 1.2 \text{ TeV}.$$

The sensitivity will improve further when the LHC starts to run at a center of mass energy of $\sqrt{s} = 14 \text{ TeV}$ and a higher luminosity in 2015. The upper bound of the parameter α_4 at 95% CL for an integrated luminosity of $\int L dt = 300 \text{ fb}^{-1}$, will be at around 0.07 which corresponds to a scale of new physics of $\Lambda \gtrsim 950 \text{ TeV}$. This number was gained from Monte Carlo studies of the upgraded experimental setup [69]. However this value is only good for a rough comparison since the unitarisation of the samples was done by another method called *clipping*.

These upper bounds can be improved further by optimizing the event selection. If a similar improvement is possible as for $\sqrt{s} = 8 \text{ TeV}$, α_4^{UL} will be at ~ 0.02 ($\Lambda \gtrsim 1.7 \text{ TeV}$).

Hence, the sensitivity is expected to increase when running the upgraded experiment. Anomalous quartic gauge couplings might be excluded or confirmed in the next run period of the LHC.

Appendix A

WZ-Analysis

Part of this diploma thesis was a contribution to the publication of the WZ cross section measurement [70, 71]. For this measurement, $\int L dt = 12.83 \text{ fb}^{-1}$ of data recorded in 2012 at a center of mass energy $\sqrt{s} = 8 \text{ TeV}$ were analyzed. Within this framework, studies of the effect of lepton isolation criteria on the significance¹ and studies of the relative systematic uncertainties of lepton reconstruction were done and will be presented in this chapter.

At first a short introduction and a brief overview of the WZ analysis shall be given in the sections A.1, A.2 and A.3. Then the results of the isolation and systematic studies shall be presented in the sections A.4 and A.5.

A.1 Introduction

In the analysis of the electroweak production of a W and a Z^2 boson (WZ EW), the focus lies on the measurement of the production cross section. The existence of anomalous electroweak couplings, a composite Higgs boson, supersymmetric particles, as well as extra vector bosons would result in an increase of the diboson production cross section predicted by the SM. Therefore, a cross section measurement can rule out or confirm models of physics beyond the SM.

At a hadron collider like the LHC, the WZ production is dominated by processes where a quark and an anti-quark are the initial states. These are at LO purely electroweak processes of the order $\mathcal{O}(\alpha_{EW}^4)$. Figure A.1 shows the most dominant Feynman diagrams for WZ production at LO.

There are four possible fully leptonic final states: $ee\nu$, $ee\mu\nu$, $\mu\mu e\nu$ or $\mu\mu\mu\nu$, where e denotes electrons and positrons, μ denotes muons and anti-muons and ν denotes neutrinos. These channels include also electrons and muons coming from taus which were produced in decays of W and Z bosons and decayed themselves due to their short life time in the order of 10^{-13} s .

Like in the $W^\pm W^\pm jj$ analysis, in the following, the term lepton will include only electrons, positrons, muons, and anti-muons.

¹There are different definitions of significances. The significance which was used in this analysis will be defined in A.4.2.

²In this chapter, when speaking of the production of a Z boson, in fact the production of Z/γ^* is meant.

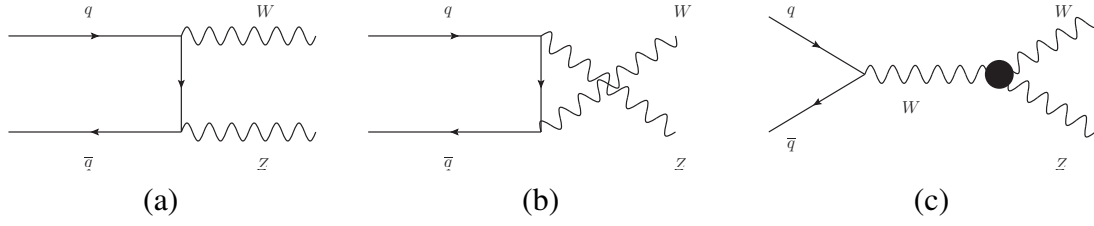


Figure A.1: Leading order Feynman diagrams of dominant processes of WZ production. Diagram (c) shows the triple gauge vertex.

A.2 Background Processes

There are SM processes that exhibit the same final states as a the decay of a W and a Z boson or can mimic this signatures in the detector due to detector effects like mis-identification or mis-reconstruction.

- **ZZ** denotes the background due to the production of two Z bosons that decay fully leptonically and where one of the four leptons is not reconstructed or does not pass the object selection. Two Z bosons can be produced in LO either in electroweak processes of order $\mathcal{O}(\alpha_{EW}^4)$ or in QCD processes of order $\mathcal{O}(\alpha_s^2 \alpha_{EW}^4)$ ³.
- **W γ** denotes the production of a W boson in association with a photon. The photon can convert into an electron-positron-pair. Hence, the signal signature is found if both particles coming from the conversion and the lepton from the W boson decay are reconstructed. as an electron through asymmetric conversion into an electron-positron-pair.
- **Z γ** denotes the the production of a Z boson in association with a photon. Due to asymmetric conversion of the photon, only one of the leptons might be reconstructed. Together with the two leptons from the Z boson decay, it mimics the signature of the signal.
- **Z+jets** stands for the production of a Z boson in association with jets. These process contributes to the background if leptons are produced in heavy quark decays or if the jets are mis-reconstructed as leptons.
- The production of a top and an anti-top quark, denoted as $t\bar{t}$ contributes to the background of WZ production if leptons from the top decays pass the object selection and a jet is mis-reconstructed as leptons. The production of a top and an anti-top and a vector boson is also included in this background. Here, leptons from the boson decay are reconstructed as well.

For a cross section measurement, the number of observed events is compared to an estimate of the number of background and signal events in a fiducial phase space. The background prediction is obtained from simulated events or, if possible, from data. If all kinematic distributions measured in simulated events and data show the same shapes and possible

³These orders take into account the electroweak decay of the Z bosons.

	Electrons	Muons
reconstruction algorithms	electron reconstruction	SegmentTagged, Combined
quality criterion	loose++	loose
p_T	$> 15 \text{ GeV}$	$> 15 \text{ GeV}$
$ \eta $	< 2.47	< 2.5
	not $1.37 < \eta < 1.52$	
track isolation $p_T^{\text{cone}}(0.2)/p_T^{\text{track}}$	< 0.13	< 0.15
calorimeter isolation $E_T^{\text{cone}}(0.2)/E_T^{\text{cluster}}$	< 0.14	
$\left \frac{d_0}{\sigma_{d_0}} \right $	< 6	< 3
$ z_0 \cdot \sin(\theta) $	$< 0.5 \text{ mm}$	$< 0.5 \text{ mm}$

Table A.1: List of pre-selection criteria of electrons and muons used in the cross section measurement. For the Selection of the W and Z candidates, harder object cuts are applied (see following section).

deviations are well understood, the cross section of the WZ process can be evaluated using the profile Likelihood method as it was done in the $W^\pm W^\pm jj$ analysis described in Chapter 7.8.1. Hence, the systematic uncertainties are taken into account and the measured cross section is the best fit value when fitting the function to the data.

For a precise measurement a precise knowledge of the number of background events is crucial. Backgrounds with at least one fake lepton are estimated from data like in the $W^\pm W^\pm jj$ analysis. This fake background is comprised of $t\bar{t}$, single top and Z +jets processes. The ZZ , $W + \gamma$ and $Z + \gamma$ background and the WZ signal are derived from MC simulation. For a detailed description of the signal and background estimation see [70] or [71].

A.3 Object and Event Selection

In order to suppress the background, selection criteria are applied to the reconstructed objects and the events.

A.3.1 Electron and Muon Selection

The selection criteria of electrons and muons which were finally used in the cross section measurement are listed in Table A.1

Due to the high masses of the W and Z bosons and the tau lepton, their decay products tend to have high momenta. Therefore, leptons with high transverse momenta are selected. The $|\eta|$ cuts ensure that only leptons with the highest tracking acceptance are chosen. For electrons, the transition region of the end cap to the barrel EM calorimeter is excluded. The isolation criteria are important to suppress secondary leptons coming from heavy quark decays and fake leptons. In Section A.4, the isolation was explained in more detail. The requirements on the longitudinal impact parameters z_0 and the d_0 significance $\left| \frac{d_0}{\sigma_{d_0}} \right|$ decrease the probability

that the selected particles did not emerge from the primary vertex. σ_{d_0} denotes the resolution of the d_0 measurement here. With these impact parameter requirements background from radioactive decays in the cavern, pile-up and cosmic muons can be rejected.

A.3.2 Event Selection

Characteristic for the WZ process are the three well isolated, high p_T leptons. Additionally a high E_T^{miss} is present which results from the neutrino coming from the W decay. With such selection criteria, the background from other SM processes can be suppressed.

The requirements that are used in the analysis are listed in the following. Prior to these, only detector related selection criteria were applied in order to ensure high quality data.

1. In order to decrease background from ZZ processes, events with 4 or more leptons passing the object selection are discarded.
2. Z candidate selection: Two leptons of the same flavor and opposite charge have to be present in the event and are required to have an invariant mass M_{ll} that fulfills $|M_{ll} - M_Z| < 10 \text{ GeV}$ where M_Z is the Z boson mass taken from PDG [6]. In the case that more than one pair of leptons fulfills the requirements of the Z candidate selected, the candidate with the invariant mass closest to the mass measured by the Particle Data Group (PDG) is taken.
3. The event has to contain exactly three leptons passing the object selection. The lepton not associated to the Z boson candidate is required to fulfill $p_T > 20 \text{ GeV}$.
4. The requirement on the missing transverse energy is: $E_T^{\text{miss}} > 25 \text{ GeV}$.
5. The transverse mass of the W boson candidate, evaluated by $M_T^2 = 2E_T^l E_T^\nu - 2\mathbf{p}_T^l \mathbf{p}_T^\nu$, has to fulfill $M_T > 20 \text{ GeV}$.

The numbers of predicted background and signal events after all cuts, are shown in Table A.2. The first uncertainty results from MC statistics and the second one is the systematic uncertainty. Additionally, the number of observed events is shown in the first line. It agrees well with the expectation within the uncertainties.

A.4 Isolation Studies

A.4.1 Lepton Isolation Variables

The isolation of tracks and calorimeter entries is an important requirement in the selection of electrons and muons. It reduces the contribution of background due to leptons resulting from hadronic decays or fake leptons (mainly produced by photons). In general, those lepton tracks have additional tracks close-by which can induce additional calorimeter cell entries close to the cluster entries associated to the electrons or the cell entries associated to the muon track.

The understanding of lepton isolation requirements will be of importance in Section A.4.2 where these requirements shall be optimized for the analysis. Therefore, the lepton isolation

Final State	eee	ee μ	e $\mu\mu$	$\mu\mu\mu$	Combined
Observed	192	270	298	334	1094
ZZ	10.3 $\pm$ 0.6	14.7 $\pm$ 0.8	12.8 $\pm$ 0.7	18.8 $\pm$ 1.0	56.6 $\pm$ 1.6
Z+jets	37 $\pm$ 3 $\pm$ 11	33 $\pm$ 4 $\pm$ 10	57 $\pm$ 4 $\pm$ 11	47 $\pm$ 5 $\pm$ 14	188 $\pm$ 8 $\pm$ 24
$t\bar{t}$ +single top		6.3 $\pm$ 0.5 $\pm$ 3.4		9.1 $\pm$ 0.7 $\pm$ 4.9	
W/Z+ γ	13 $\pm$ 3	1.3 $\pm$ 0.6	17 $\pm$ 3	–	32 $\pm$ 5
total Background	60 $\pm$ 4 $\pm$ 11	55 $\pm$ 4 $\pm$ 10	87 $\pm$ 5 $\pm$ 11	75 $\pm$ 5 $\pm$ 14	277 $\pm$ 9 $\pm$ 24
Expected signal	144 $\pm$ 12	199 $\pm$ 16	200 $\pm$ 16	276 $\pm$ 21	819 $\pm$ 34
Expected S/B	2.4	3.7	2.3	3.7	3.0

Table A.2: Overview of the observed and expected event yields after all cuts in all lepton channels and the combined channel. The first uncertainty is derived from the MC statistic and the second one results from systematic uncertainties. The expected number of signal events also includes τ contributions [70].

variables shall be defined in this section.

The calorimeter isolation E_T^{cone} is defined as the sum of calorimeter (electromagnetic and hadronic) cell entries within a circle of a radius R around the cluster or cell entry barycenter⁴ [72]. The most common radii are $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \in \{0.2, 0.3\}$ whereas $\Delta\eta$ and $\Delta\phi$ are the differences between the η and ϕ coordinates of the circle center and the circle edge respectively. For electron candidates, the energy from the 5×7 cell grid around the cluster barycenter is removed for in order to count only entries that have been induced by other objects than the object of interest. For muons, the energy loss in the inner detector (ID) is subtracted. The following equations describes the calculation of the *calorimeter isolation* for electrons and muons:

$$\text{Electrons:} \quad E_T^{\text{cone}}(R) = \left(\sum_{\substack{\text{cells} \\ \Delta R' < R}} E_T(\text{cell}) \right) - E_T(5 \times 7 \text{ cells}) \quad (\text{A.1})$$

$$\text{Muons:} \quad E_T^{\text{cone}}(R) = \left(\sum_{\substack{\text{cells} \\ \Delta R' < R}} E_T(\text{cell}) \right) - E_T(\text{ID}) \quad (\text{A.2})$$

The *track isolation* is defined by the sum over the p_T of all ID tracks within a cone of radius R with the lepton candidate track on its axis:

$$p_T^{\text{cone}}(R) = \sum_{\substack{\text{good tracks} \\ \text{track} \neq \text{lepton} \\ \Delta R' < R}} p_T(\text{track}) \quad (\text{A.3})$$

⁴The circle can be seen as the area of a cone whose tip is at the primary vertex and whose axis is approximated by the track of the particle of interest (also referred to as isolation cone).

In this calculation only *good* tracks are taken into account which are defined by the following requirements:

- $p_T > 0.4 \text{ GeV}$
- $|d_0| < 1.5 \text{ mm}$
- $|z_0| < 1.0 \text{ mm}$ (only applied to electrons)
- at least one hit in the b-layer
- at least 9 hits in the silicon tracker
- no holes (dead or not triggered sensors) on the pixel detector track

These criteria ensure that the tracks inside the cone come from the same vertex as the lepton candidate itself. Therefore, the influence of pile-up on the track isolation is small.

In general, relative isolation criteria are used in order to take into account that a higher energetic lepton radiates more bremsstrahlung when traveling through detector material. This can lead to pair production and hence, to tracks close to the lepton track. These additional tracks can result in additional entries in the EM calorimeter around the associated cluster as well. Therefore, the calorimeter isolation variable and the track isolation variable are divided by the energy of the lepton or the transverse momentum of the lepton track. In the following, the ratio $E_T^{\text{cone}}(R_0)/E_T^{\text{lepton}}$ will be referred to as CI_i and $p_T^{\text{cone}}(R_0)/p_T^{\text{track}}$ as TI_i with $i \in \{e, \mu\}$ depending if electron or muon isolations are considered.

A.4.2 Optimization of Lepton Isolation

The aim of this optimization study is the determination of the influence of lepton isolation criteria on the object selection. For this study, all background contributions were estimated from MC simulations. No data driven estimation was conducted since at the time the optimization was done, they were not yet finalized. In order to improve the isolation criteria, the requirements were varied and the whole event selection was run again. As a figure of merit the relation $\sqrt{S+B}/S$ was chosen. S stands for the number of signal events and B for the total number of background events. This figure of merit evaluates the uncertainty of the measurement relative to the number of signal events since for Poisson statistics the uncertainty is given by the square root of the number of measured events. The aim of the optimization is to minimize $\sqrt{S+B}/S$ in order to get a smaller uncertainty on the measurement.

Influence of the Cone Size

As a first step, the effect of varying the cone size R of the track and calorimeter isolation shall be studied. The configuration $TI_e < 0.13$, $CI_e < 0.14$ and $TI_\mu < 0.15$ is tested for the cone sizes $R = 0.2$ and $R = 0.3$. Both are recommendations of the MCP and Egama groups. Table A.3 shows the corresponding event yields for the background, the signal and the values for the figure of merit. The given uncertainties are derived from MC statistics.

	$R_0 = 0.3$	$R_0 = 0.2$
Z+jets	142.27 ± 17.36	187.22 ± 19.82
ZZ	271.24 ± 3.32	140.58 ± 3.45
$t\bar{t}$	29.03 ± 1.37	43.85 ± 1.89
WZ	880.02 ± 8.32	922.32 ± 7.55
$\sqrt{S+B}/S$	3.90 %	3.90%

Table A.3: Comparison of the event yields for the two different cone sizes $R_0 = 0.2$ and $R_0 = 0.3$ for $TI_e < 0.13$, $CI_e < 0.14$ and $TI_\mu < 0.15$. Just the main background contributions are listed here.

It is not surprising that the number of selected events increases when a smaller cone size is selected. A smaller cone size means that less additional tracks and cell entries are taken into account and therefore, p_T^{cone} and E_T^{cone} are smaller. Hence, the isolation criterion is looser. For the smaller cone size, the signal increases by about 6% and the two biggest background contributions Z+jets and ZZ increase by 31% and 8% respectively. The signal to background ratio decreases from 2.9 for $R = 0.3$ to 2.47 for $R = 0.2$. Hence, $R = 0.3$ has higher background rejection.

$\sqrt{S+B}/S$ is the same for both cone sizes. Therefore, using this variable, it is not possible to decide which cone size is superior.

When taking into account that S and B have statistical uncertainties from MC those can be added to the uncertainty of the measurement. The figure of merit then changes to

$$F = \frac{\sqrt{S+B+\Delta S^2+\Delta B^2}}{S} \quad (\text{A.4})$$

This results in the following numbers for the two selections with the different cone sizes:

$$\begin{aligned} R = 0.2 : \quad F &= 4.55\% \\ R = 0.3 : \quad F &= 4.48\%. \end{aligned} \quad (\text{A.5})$$

A selection with $R = 0.3$ results in a smaller uncertainty on the measurement when taking into account the uncertainty of the MC statistics. However, the difference is in the order of 0.07% which is also the order of statistical fluctuations. Hence, neither $R = 0.2$ nor $R = 0.3$ applied to all three isolation variables (TI_e , TI_μ , and CI_e) is more beneficial for the selection.

Optimization of Isolation Cut Values

In a second step, the influence of changing the cut values of TI_e , TI_μ and CI_e on the uncertainty of the measurement is studied. In the following the radius of the cone size is set to $R_0 = 0.2$. For each isolation cut configuration, the ratio $\sqrt{S+B}/S$ was calculated. A starting configuration was chosen, which is shown in blue in the Tables A.4 (A) and (B). In the lines beneath only the changed isolation cut values with respect to the starting configuration are listed. These were changed by 20% or 10% with respect to the nominal value. The lines in red indicate the cut values that induced a lower $\sqrt{S+B}/S$ than the starting configuration.

TI_e	CI_e	TI_μ	$\sqrt{S+B}/S$
0.13	0.14	0.15	0.03898
0.156			0.03918
0.104			0.03883
	0.168		0.03901
	0.112		0.03891
		0.18	0.03932
		0.12	0.03897

(A)

TI_e	CI_e	TI_μ	$\sqrt{S+B}/S$
0.104	0.112	0.12	0.03880
0.183			0.03910
0.125			0.03886
	0.099		0.03883
	0.134		0.03884
		0.069	0.03871
		0.134	0.03878

(B)

Table A.4: Summary of different isolation cut sets with the corresponding $\sqrt{S+B}/S$. The nominal configuration is shown in blue. The lines beneath the nominal configuration show only the changed cut values with respect to the nominal configuration. In Table B the nominal configuration was constructed from the cut values that lead to a smaller $\sqrt{S+B}/S$ in Table A (shown in red).

The cut values that lead to a decrease of $\sqrt{S+B}/S$ in Table A.4(A) were taken as new starting configuration in Table A.4(B).

This procedure was conducted in several iteration steps. The optimized configuration with the event yields of all background and signal contributions is shown in Table A.5. For comparison the event yields for the nominal configuration are shown as well.

The background contribution of Z+jets decreases significantly by about 50% when applying the new isolation criteria. By tightening the isolation cuts, the chance that a lepton coming from hadronic decays is reduced which is why the $t\bar{t}$ background is decreased by almost 50% as well. The number of signal events in the optimized configuration is only reduced by 4% with respect to the nominal configuration.

This results in a higher signal to background ratio compared to the nominal configuration. $\sqrt{S+B}/S$ is 2% smaller and F is 6% smaller for the optimized cut set. For $\sqrt{S+B}/S$ this is within the statistical fluctuations. For F , which takes into account the MC statistics, the difference is larger. Since this variable is more trustworthy, one can conclude that the isolation selection has been successfully optimized.

A.4.3 Conclusions

It was shown that the effect of changing the isolation cone size from $R = 0.3$ to $R = 0.2$ on the uncertainty of the measurement is negligibly small. However, $R = 0.2$ seems to have a higher background rejection capability and in general it is more pile-up resistant since the probability of pile-up tracks lying inside the cone is smaller. Therefore, in the WZ analysis, the cone size $R = 0.2$ was finally used.

The optimization of the lepton isolation requirements was successful as well as it resulted in a decreased background yield and a smaller measurement uncertainty when taking into account the MC statistics. Nevertheless a check of some kinematic distributions would be reasonable in order to find out whether the tighter isolation requirements have undesired effects on them. This would have been the next step in the optimization procedure. However,

	Optimized Configuration	Nominal Configuration
	$R = 0.2$	$R = 0.2$
	$TI_e < 0.065$	$TI_e < 0.13$
	$CI_e < 0.12$	$CI_e < 0.14$
	$TI_\mu < 0.076$	$TI_\mu < 0.15$
Z+jets	98.07 ± 14.34	187.22 ± 19.82
ZZ	132.52 ± 3.36	139.86 ± 3.45
$t\bar{t}$	27.19 ± 1.20	43.85 ± 1.89
WZ	884.11 ± 7.39	922.32 ± 7.55
$\sqrt{S+B}/S$	3.82%	3.90%
F	4.26%	4.55%
S/B	3.4%	2.5%

Table A.5: Comparison between optimized (final) and nominal configuration of isolation cuts. Just the main background contributions are listed here.

due to time constraints the nominal isolation requirements have been applied in the end as such studies had already been done for them.

In these studies, the fake background was estimated from MC samples. Therefore, primary a tendency of the changed object selection can be extracted from the results. In order to obtain more precise numbers, the fake background should be estimated from data since the simulation might not model this backgrounds accurately.

A.5 Studies on Lepton Systematic Uncertainties

In the evaluation of the cross section using a Likelihood fit, all systematic uncertainties of the signal and background estimation are taken into account by Gaussian constraints. They influence the width of the profile Likelihood function and hence contribute to the uncertainty of the measured cross section.

The sources of systematic uncertainties for the $W^\pm W^\pm jj$ analysis are listed in Section 7.4 and are the same for the WZ analysis. The focus of this study lies on the evaluation of uncertainties resulting from the lepton reconstruction. These corrections that are applied to the MC samples were described in Section 5.2. If not stated otherwise, the influence of the uncertainties of the correction factors applied in the lepton reconstruction are investigated by varying the factors up- and downwards within their 1σ uncertainties. Hence, the proportion of events affected such that they migrate in or out of the selected phase space due to the variation is obtained.

A.5.1 Muon Systematic Uncertainties

Table A.6 summarizes the relative uncertainties resulting from the muon reconstruction. If not signed with plus and minus, the mean values of the effects due to the upwards and downwards variations are given. For those, the number of events vary symmetrically around the

Uncertainty per channel [%]	μee	$\mu\mu e$	$\mu\mu\mu$
Reconstruction efficiency	0.3	0.57	0.87
p_T smearing: ID	0.01	0.06	0.04
MS	0.04	0.04	0.03
Scale	0.01	0.02	0.02
combination	0.04	0.08	0.05
Isolation & Impact Parameter Efficiency	$\pm_{0.53}^{0.53}$	$\pm_{1.24}^{1.25}$	$\pm_{1.72}^{1.74}$
Total	1.94	1.38	0.87

Table A.6: Summary of muon systematic uncertainties on the expected event yields in MC signal samples.

nominal values and scales reasonably well with the number of muons in each decay channel because the correction factors are applied to each muon separately.

The scale and resolution systematic uncertainties for muons are different for the ID and the MS. Hence, the uncertainties are given for these two detector regions separately.

The p_T scale accounts for the discrepancy between the simulated and the observed muon p_T spectrum. The effect of this scale is obtained by switching the correction on and off and is considered as a systematic uncertainty.

The row named “combination” in Table A.6 is the sum in quadrature of the ID-, MS- and scale systematic uncertainties. It should scale with the number of muons in the channel but is largest for the $\mu\mu e$ channel. This can be explained by statistical fluctuations.

The uncertainty of the impact and isolation parameter efficiency scales with the number of muons in the decay channel and is the largest contribution to the total systematic uncertainty.

A.5.2 Electron Systematic Uncertainties

The values for the relative uncertainties of the electron systematics can be found in Table A.7. Like in the muon case, the uncertainties scale with the number of electrons in the channel since they are applied to each electron separately.

The contribution of the identification efficiency is the largest one which can be explained by the relatively high probability that electrons are faked by photons and jets.

A.5.3 Discussion

When comparing the systematic uncertainties of muons and electrons it can be easily noticed that the uncertainties for muons are significantly smaller than the ones for electrons. The biggest difference comes from the reconstruction and identification efficiency. The uncertainties for these corrections are larger for electrons than for muons. This indicates that the reconstruction of muons is much more precise than for electrons.

When reconstructing electron candidates, the probability of having reconstructed another particle as an electron candidate is not negligible because the signals in the ID and in the

Uncertainty per channel [%]	eee	ee μ	e $\mu\mu$
Reconstruction efficiency	2.0	1.4	0.7
Identification efficiency	3.2	2.0	1.1
Energy smearing	0.2	0.2	0.1
Energy Scale	0.6	0.4	0.2
Isolation & Impact Parameter Efficiency	0.6	0.4	0.2
Total	3.9	2.5	1.3

Table A.7: Summary of electron systematic uncertainties on the expected event yields in MC signal samples

calorimeters are very dense and are not always easily separated.

Muons are only reconstructed if a signal in the MS is present. The probability that another particle than a muon can leave a signature in the MS is very small. However, in some cases it is difficult to associate a track of the ID to the MS signal. Therefore, the uncertainties on the isolation and impact parameter efficiency are the largest ones.

Appendix B

Mathematical Utilities

B.1 Correlation Coefficient of random variables

The correlation coefficient of two random variables X and Y is defined by

$$C(X, Y) = \frac{\text{Cov}(X, Y)}{\sigma(X)\sigma(Y)}, \quad (\text{B.1})$$

with σ being the positive standard deviation and $\text{Cov}(X, Y)$ the covariance. The covariance is defined by

$$\text{Cov}(X, Y) = E[(X - E(X)) \cdot (Y - E(Y))], \quad (\text{B.2})$$

where E denotes the expectation value.

The covariance is positive if high (low) values of X are accompanied by high (low) values of Y and it is negative if high values of one random variable is accompanied by low values of the other variable and vice versa. If it is zero, no connection between X and Y is given. If $C(X, Y) = (-)1$ one speaks of 100% (anti-)correlation between X and Y .

B.2 Bilinear Interpolation

Given four fixed points $P_{11} = (x_1, y_1)$, $P_{12} = (x_1, y_2)$, $P_{21} = (x_2, y_1)$, and $P_{22} = (x_2, y_2)$. A function $f(x, y)$ can be approximated if $x_1 \leq x \leq x_2$ and $y_1 \leq y \leq y_2$ by

$$f(x, y) \approx \frac{y_2 - y}{y_2 - y_1} \cdot \left(\frac{x_2 - x}{x_2 - x_1} f(P_{11}) + \frac{x - x_1}{x_2 - x_1} f(P_{21}) \right) \quad (\text{B.3})$$

$$+ \frac{y - y_1}{y_2 - y_1} \left(\frac{x_2 - x}{x_2 - x_1} f(P_{12}) + \frac{x - x_1}{x_2 - x_1} f(P_{22}) \right). \quad (\text{B.4})$$

Appendix C

Measurement of aQGC in $W^\pm W^\pm$ Scattering

C.1 Monte Carlo Background Samples

The MC samples used for the background estimation are given in the Tables C.1, C.2, C.3, and C.4.

Process	DataSet ID	σ [pb]	k -factor	filer EF
$W\gamma$				
$W\gamma\text{Np0}$	146436	230.1	1.15	0.31372
$W\gamma\text{Np1}$	146437	59.34	1.15	0.44871
$W\gamma\text{Np2}$	146438	21.47	1.15	0.54461
$W\gamma\text{Np3}$	146439	7.103	1.15	0.62974
$W\gamma\text{Np4}$	146434	2.122	1.15	1.0
$W\gamma\text{Np5}$	146435	0.4661	1.15	1.0

Table C.1: $W\gamma$ Background Samples for the $W^\pm W^\pm$ analysis

Process	DataSet ID	σ [pb]	k -factor	filer EF
Diboson Production				
$W^\pm W^\mp$ EW	147193	0.09588	1.0	1.0
$WZ \rightarrow ll\nu$ EW	147194	0.07296	0.67	1.0
$ZZ \rightarrow ll\nu\nu$ EW	161982	0.0041	1.0	1.0
$ZZ \rightarrow ll ll$ EW	147196	0.00691	1.0	1.0
$W^\pm W^\mp$ QCD	126892	5.4982	1.06	1.0
$WZ \rightarrow ll\nu$ QCD	126893	9.7570	1.18	1.0
	147197	9.7570	1.18	0.27387
$ZZ \rightarrow ll\nu\nu$ QCD	126895	0.4962	1.05	1.0
$ZZ \rightarrow ll ll$ QCD	126894	8.7345	1.0	1.0
$t\bar{t}$ Production				
$t\bar{t} \rightarrow ll\nu\nu qq$	110001	238.06	1.0	0.105
$t\bar{t} \rightarrow ll\nu\nu qq$	105200	238.06	1.0	0.543
$t\bar{t} \rightarrow qq$	105204	238.06	1.0	0.457
$t\bar{t} + W$	119353	0.1041	1.18	1.0
$t\bar{t} + Wj$	119354	0.0932	1.18	1.0
$t\bar{t} + Wj$ excl.	174830	0.053372	1.18	1.0
$t\bar{t} + Wjj$ incl.	174831	0.041482	1.18	1.0
$t\bar{t} + Z$	119355	0.067690	1.34	1.0
$t\bar{t} + Zj$	119356	0.0874	1.34	1.0
$t\bar{t} + Zj$ excl.	174832	0.045357	1.34	1.0
$t\bar{t} + Zjj$ incl.	174833	0.039772	1.34	1.0
single top Production				
s-channel: $t \rightarrow b e \nu$	108343	0.606	1.0	1.0
s-channel: $t \rightarrow b \mu \nu$	108344	0.606	1.0	1.0
s-channel: $t \rightarrow b \tau \nu$	108345	0.606	1.0	1.0
t-channel: $t \rightarrow b W$ incl.	108346	22.37	1.0	1.0
t-channel: $t \rightarrow b e \nu$	117360	9.48	1.0	1.0
t-channel: $t \rightarrow b \mu \nu$	117361	9.48	1.0	1.0
t-channel: $t \rightarrow b \tau \nu$	117362	9.48	1.0	1.0

Table C.2: Diboson and $t\bar{t}$ background samples for the $W^\pm W^\pm$ analysis

Process	DataSet ID	σ [pb]	k -factor
Z+jets, filer EF = 0			
ZeeNp0	107650	712.0	1.23
ZeeNp1	107651	155.0	1.23
ZeeNp2	107652	48.8	1.23
ZeeNp3	107653	14.2	1.23
ZeeNp4	107654	3.77	1.23
ZeeNp5	107655	1.12	1.23
ZmumuNp0	107660	712.0	1.23
ZmumuNp1	107661	155.0	1.23
ZmumuNp2	107662	48.8	1.23
ZmumuNp3	107663	14.2	1.23
ZmumuNp4	107664	3.77	1.23
ZmumuNp5	107665	1.12	1.23
ZtautauNp0	107670	712.0	1.23
ZtautauNp1	107671	155.0	1.23
ZtautauNp2	107672	48.8	1.23
ZtautauNp3	107673	14.2	1.23
ZtautauNp4	107674	3.77	1.23
ZtautauNp5	107675	1.12	1.23
ZeebbNp0	109300	8.378	1.23
ZeebbNp1	109301	3.253	1.23
ZeebbNp2	109302	1.190	1.23
ZeebbNp3	109303	0.503	1.23
ZmumubbNp0	109305	8.374	1.23
ZmumubbNp1	109306	3.254	1.23
ZmumubbNp2	109307	1.181	1.23
ZmumubbNp3	109308	0.507	1.23
ZtautauNp0	109310	8.376	1.23
ZtautauNp1	109311	3.243	1.23
ZtautauNp2	109312	1.194	1.23
ZtautauNp3	109313	0.498	1.23
ZecccNp0	126414	15.654	1.23
ZecccNp1	126415	6.8946	1.23
ZecccNp2	126416	2.9204	1.23
ZecccNp3	126417	1.1411	1.23
ZmumuccNp0	126418	15.649	1.23
ZmumuccNp1	126419	6.8930	1.23
ZmumuccNp2	126420	2.9176	1.23
ZmumuccNp3	126421	1.1377	1.23
ZtautauNp0	117706	15.652	1.23
ZtautauNp1	117707	6.8979	1.23
ZtautauNp2	117708	2.9100	1.23
ZtautauNp3	117709	1.1340	1.23

Table C.3: Z+jets samples for the $W^\pm W^\pm$ analysis

Process	DataSet ID	σ [pb]	k -factor
W+jets, filer EF = 0			
WenuNp0	107680	8037.1	1.18
WenuNp1	107681	1579.2	1.18
WenuNp2	107682	477.2	1.18
WenuNp3	107683	133.9	1.18
WenuNp4	107684	35.65	1.18
WenuNp5	107685	10.55	1.18
WmunuNp0	107690	8040.0	1.18
WmunuNp1	107691	1580.3	1.18
WmunuNp2	107692	477.5	1.18
WmunuNp3	107693	133.9	1.18
WmunuNp4	107694	35.64	1.18
WmunuNp5	107695	10.57	1.18
WtaunuNp0	107700	8035.8	1.18
WtaunuNp1	107701	1579.8	1.18
WtaunuNp2	107702	477.6	1.18
WtaunuNp3	107703	133.8	1.18
WtaunuNp4	107704	35.6	1.18
WtaunuNp5	107705	10.5	1.18
WccNp0	117284	8035.8	1.18
WccNp1	117285	1579.8	1.18
WccNp2	117286	477.6	1.18
WccNp3	117287	133.8	1.18
WcNp0	117293	807.9	1.18
WcNp1	117294	267.6	1.18
WcNp2	117295	69.8	1.18
WcNp3	117296	20.6	1.18
WcNp4	117297	4.3	1.18
WbbNp0	117280	55.7	1.18
WbbNp1	117281	45.2	1.18
WbbNp2	117282	23.3	1.18
WbbNp3	117283	11.1	1.18

Table C.4: W+jets samples for the $W^\pm W^\pm$ analysis

C.2 Event Cleaning cuts

- A Good Run List (GRL) is applied:
data12_8TeV.periodAllYear_DetStatus-v61-pro14-02_DQDefects-00-01-00_PHYS_StandardGRL_All_Good.xml
- Trigger matching, trigger chains: EF_e24vhi_medium1, EF_e60_medium1, EF_mu24i_tight, and EF_mu36_tight
- Pile-up Reweighting, Vertex Reweighting
- Calorimeter quality flags are required to be good (LarError !=2 and TileError !=2)
- Electrons have to fulfill the e/gamma quality requirements
- Events with a jet pointing to a hot tile cell in periods B1 and B2 are rejected
- Events with a selected identified as bad by the IsLooserBadJet algorithm provided by the Jet/ETmiss group are vetoed
- Incomplete events are discarded by requiring (coreFlags & 0x40000) = 0
- At least one vertex has to be reconstructed from at least 3 tracks with a p_T larger than 0.5 GeV

C.3 Object Definitions

C.3.1 Muons

The muon object definitions used in the nominal analysis, the third lepton veto and the estimation of the fake background are summarized in Table C.5.

C.3.2 Electrons

The electron object definitions used in the nominal analysis, the third lepton veto and the estimation of the fake background are summarized in Table C.6.

C.3.3 Tag Electron Definition in the Tag-and-Probe Method

In the $W^\pm W^\pm jj$ analysis the tag-and-probe method is used in order to estimate the charge misID background. The tag electron is defined by the following criteria additional to the nominal requirements:

- $d_0/\sigma_{d_0} < 1.5$
- $|\eta| < 2.0$
- Number of hits in the silicon tracker > 9

Nominal Analysis	Third Lepton Veto	Fake Estimation
combined STACO	loose STACO	combined STACO
$p_T > 25 \text{ GeV}, \eta < 2.5$	$p_T > 6 \text{ GeV}, \eta < 2.5$	$p_T > 25 \text{ GeV}, \eta < 2.5$
nBLayerHits > 0 if BLayerHits are expected nPixHits + nPixelDeadSensors ≥ 1 nSCTHits + nSCTDeadSensors ≥ 5 nPixHoles + nSCTHoles ≤ 2 (nTRTOutliers+nTRTHits) ≥ 6 and nTRTOutliers/(nTRTOutliers+nTRTHits) < 0.9 for $0.1 < \eta < 1.9$ Otherwise (nTRTOutliers/(nTRTOutliers+nTRTHits) < 0.9 and (nTRTOutliers+nTRTHits) ≥ 6) or (nTRTOutliers+nTRTHits) < 6)		
$ z_0 \cdot \sin\theta < 0.5 \text{ mm}$ $\frac{d_0}{\sigma_{d_0}} < 3$	$ z_0 \cdot \sin\theta < 0.5 \text{ mm}$ $\frac{d_0}{\sigma_{d_0}} < 3$	$ z_0 \cdot \sin\theta < 5 \text{ mm}$ $\frac{d_0}{\sigma_{d_0}} < 10$
$p_T^{\text{cone}}(0.3)/p_T^{\text{track}} < 0.07$ $E_T^{\text{cone}}(0.3)/E_T < 0.07$	$p_T^{\text{cone}}(0.3)/p_T^{\text{track}} < 0.15$ -	$p_T^{\text{cone}}(0.3)/p_T^{\text{track}} < 2.0$ $E_T^{\text{cone}}(0.3)/E_T < 2.0$

Table C.5: Object definitions of muons

- At least one B-layer hit
- The tag lepton must be the one that activated one of the analysis triggers.

C.3.4 Jets

- reconstructed with anti- k_T algorithm, cone size: $R = 0.4$
- calibrated from the electromagnetic energy scale to the hadronic scale by applying a correction factor which depending on E_T and η
- $p_T > 30 \text{ GeV}$ at the hadronic energy scale
- $|\eta| < 4.5$
- JVF > 0.5 for jets with $|\eta| < 2.4$ and $p_T < 50 \text{ GeV}$

C.4 Overview of Optimizations

Table C.7 shows all two and tree dimensional optimizations done during this work and the corresponding best cut set with the optimized expected limits in α_4 and α_5 . If several cut sets lead to the same limits, the cut set with the highest number of signal events (SM WHIZARD Sample) was chosen as the best cut set in order to reduce statistical uncertainties.

Nominal Selection	Third Lepton Veto	Fake Estimation
$E_T > 25 \text{ GeV}$	$E_T > 7 \text{ GeV}$	$E_T > 25 \text{ GeV}$
$ \eta < 2.47$, not $1.37 \leq \eta \leq 1.52$		
Object Quality: el author == 1 el author == 3, el OQ&1446 == 0		
ID criterion: tight++	ID criterion: loose++	ID criterion: loose++
$ z_0 < 0.5 \text{ mm}$ $\frac{d_0}{\sigma_{d_0}} < 3$	$ z_0 < 0.5 \text{ mm}$ $\frac{d_0}{\sigma_{d_0}} < 3$	$ z_0 < 5 \text{ mm}$ $\frac{d_0}{\sigma_{d_0}} < 10$
$p_T^{\text{cone}}(0.3)/E_T^{\text{cluster}} < 0.06$ $E_T^{\text{cone}}(0.3)/E_T^{\text{cluster}} < 0.14$	$p_T^{\text{cone}}(0.3)/E_T^{\text{cluster}} < 0.13$ -	$0.06 < p_T^{\text{cone}}(0.3)/E_T^{\text{cluster}} < 2$ $0.14 < E_T^{\text{cone}}(0.3)/E_T^{\text{cluster}} < 2$

Table C.6: Object definitions of electrons

constant variables	optimized variables	best cut set	α_4^{UL}	α_5^{UL}	S	B
$\Delta Y_{\text{jj}} = 2.4$	$\Delta\phi_{\text{ll}}, \Sigma p_{\text{T}}^{\text{ll}}, M_{\text{jj}}^{\text{ll}}$	$\{2.25, 250 \text{ GeV}, 400 \text{ GeV}\}$	0.05	0.09	0.80	0.70
$M_{\text{jj}} = 150 \text{ GeV}$	$\Delta Y_{\text{jj}}, \Delta\phi_{\text{ll}}, \Sigma p_{\text{T}}^{\text{ll}}$	$\{3.5, 2.25, 250 \text{ GeV}\}$	0.04	0.09	0.47	0.52
$M_{\text{jj}} = 150 \text{ GeV}$	$\Delta Y_{\text{jj}}, \Delta\phi_{\text{ll}}, \Sigma p_{\text{T}}^{\text{ll}}$ (finer scan)	$\{3.25, 1.8, 250 \text{ GeV}\}$	0.04	0.09	0.71	0.75
$M_{\text{jj}} = 300 \text{ GeV}$	$\Delta Y_{\text{jj}}, \Delta\phi_{\text{ll}}, \Sigma p_{\text{T}}^{\text{ll}}$	$\{3.0, 2.25, 250 \text{ GeV}\}$	0.04	0.09	0.66	0.73
$M_{\text{jj}} = 500 \text{ GeV}$	$\Delta Y_{\text{jj}}, \Delta\phi_{\text{ll}}, \Sigma p_{\text{T}}^{\text{ll}}$	$\{3.0, 1.00, 200 \text{ GeV}\}$	0.05	0.10	1.64	1.39
$M_{\text{jj}} = 500 \text{ GeV}, \Delta Y_{\text{jj}} = 2.4$	$\Delta\phi_{\text{ll}}, \Sigma p_{\text{T}}^{\text{ll}}$	$\{1.75, 200 \text{ GeV}\}$	0.05	0.10	1.71	1.33
$M_{\text{jj}} = 500 \text{ GeV}, \Delta Y_{\text{jj}} = 2.4, \Delta\phi_{\text{ll}} = 0$	$\Sigma p_{\text{T}}^{\text{ll}}$	$\{200 \text{ GeV}\}$	0.06	0.11	2.49	2.31

Table C.7: Summary of the best cut sets and their corresponding limits in α_4 and α_5 found in different optimizations.

List of Figures

2.1	Feynman diagrams of the muon decay	12
2.2	Relative interference of the SM and the aQGC cross section	15
2.3	Cross section of $W^\pm W^\pm$ scattering	16
2.4	Illustration of the K-matrix unitarization method	18
3.1	The LHC accelerator complex	20
3.2	Overview of the ATLAS detector	22
3.3	Layout of the ATLAS inner detector	23
3.4	Schematic view of the ATLAS calorimeter system	24
3.5	Schematic view of the ATLAS muon spectrometer	25
6.1	Scheme of the scattering of two vector bosons	39
6.2	Schematic view of the VBS WW topology	40
6.3	Feynman diagrams of VBS processes	41
6.4	Non-VBS Feynman diagrams of $VVjj$ EW processes	42
6.5	Feynman diagrams of $VVjj$ QCD processes	42
7.1	Display of an observed event with $W^\pm W^\pm jj$ topology	45
7.2	Charge misID rates	48
7.3	Electron and muon fake factors	49
7.4	Cross section dependence on α_4 and α_5	59
7.5	Dependence of the acceptance and the efficiency on α_4 and α_5	60
7.6	Fiducial cross section in dependence on α_4 and α_5	61
7.7	Jet kinematic distributions	63
7.8	Lepton kinematic distributions	64
7.9	Two dimensional kinematic distributions	67
7.10	Illustration of a 90% symmetric confidence interval	69
7.11	Test statistic in dependence of the signal strength μ	72
7.12	Two dimensional contours of expected and observed constraints	73
7.13	Dependence of the limits on cuts in M_{jj} , ΔY_{jj} , $\sum p_T^{\text{ll}}$, and $\Delta\phi_{\text{ll}}$	75
7.14	Comparison of observation and background prediction	76
7.15	Dependence of the limits on cut in $\Delta\phi_{\text{ll}}$ and $\sum p_T^{\text{ll}}$	77
7.16	Comparison of observation and background prediction for the optimal cut set	80
A.1	Leading order Feynman diagrams of WZ production	86

List of Tables

2.1	Overview of the Standard Model fermions	4
2.2	Overview on the Standard Model bosons	5
2.3	Overview on the Standard Model symmetry groups	6
2.4	Summary of fermions fields and their associated EW quantum numbers	6
7.1	EW and QCD production cross sections of $W^\pm W^\pm$ and $W^\pm W^\mp$	44
7.2	Summary of systematic uncertainties in the fiducial phase space.	55
7.3	Summary of expected and observed event yields after all cuts	56
7.4	Summary of officially produced WHIZARD samples	58
7.5	Summary of correlation coefficients	66
7.6	List of confidence levels and the corresponding lower bounds on t_μ	69
7.7	Summary of expected and observed 1D constraints	72
7.8	Cut sets of $\Delta\phi_{ll}$ and $\sum p_T^l$ that resulted in the best constraints.	77
7.9	Comparison of acceptance and efficiency ratios of different cut sets	78
7.10	Best cut sets of ΔY_{jj} , $\Delta\phi_{ll}$, and $\sum p_T^l$	79
7.11	Comparison of the limits of the best cut set to nominal selection	82
A.1	List of pre-selection criteria of electrons and muons	87
A.2	Overview of observed and expected event yields	89
A.3	Comparison of the event yields for two different cone sizes	91
A.4	Summary of different isolation cut sets with the corresponding $\sqrt{S+B}/S$	92
A.5	Comparison between optimized and nominal configuration of isolation cuts	93
A.6	Summary of muon systematic uncertainties	94
A.7	Summary of electron systematic uncertainties	95
C.1	$W\gamma$ Background Samples for the $W^\pm W^\pm$ analysis	99
C.2	Diboson and $t\bar{t}$ background samples for the $W^\pm W^\pm$ analysis	100
C.3	Z+jets samples for the $W^\pm W^\pm$ analysis	101
C.4	W+jets samples for the $W^\pm W^\pm$ analysis	102
C.5	Object definitions of muons	104
C.6	Object definitions of electrons	105
C.7	Summary of best cut sets of different optimizations	106

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Danksagung

An dieser Stelle möchte allen meinen Dank aussprechen, die zum Gelingen dieser Arbeit und meines Studiums beigetragen haben.

Ein besonderer Dank geht an Prof. Michael Kobel für die Herausgabe dieses spannenden und aktuellen Themas, seine gute Betreuung und lebhaften Diskussionen.

Des Weiteren möchte ich den Doktoranden der VBS Arbeitsgruppe danken, die mir mit Rat und Tat zur Seite standen, diese Arbeit Korrektur gelesen haben und die dafür sorgten, dass ich gern das Büro E20 betrat. Speziell danke ich Christian Gumpert für ein ständig offenes Ohr bei technischen und statistischen Fragen und der Suche nach Käfern im Programmiercode, Ulrike Schnoor für ihren Beistand im Irrgarten der Effektiven Feldtheorien und anomalen Kopplungen und ihre zauberhaften Samples und Felix Socher und Philipp Anger für ihre Betreuung bei den Isolationen und Unsicherheiten der WZ Analyse.

Ebenfalls danke ich Anja Vest für das Korrekturlesen dieser Arbeit und diesbezügliche wertvolle Ratschläge.

Ein spezieller Dank geht an meine Eltern für ihre moralische und finanzielle Unterstützung während meiner gesamten Studienzeit, ohne die dieser Abschluss nicht möglich gewesen wäre. Für sie stand meine Ausbildung immer an erster Stelle. Im Besonderen danke ich ihnen für die Ermöglichung meines Auslandsaufenthaltes in Frankreich, wo ich meine Leidenschaft für die Arbeit in der Wissenschaft entdeckte.

An dieser Stelle möchte ich auch meinen Freunden Christian, Dani, Maria und Lilly danken, für offene Ohren und Türen und eine lebendige Studienzeit.

Besonderer Dank geht an Christian Schreck, der mich mit viel Verständnis, leckeren Abendessen und dem richtigen Maß an Ablenkung unterstützte.

Erklärung

Hiermit versichere ich, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht. Die Arbeit wurde bisher weder im Inland noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

Constanze Hasterok
Dresden, den 29.10.2013