Search for new physics in vector boson scattering with the CMS experiment in the all-jets final state

(Suche nach neuer Physik in Vektorboson-Streuung mit dem CMS Experiment in Endzuständen mit Jets)

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- 1. Gutachter: Dr. Andreas Hinzmann
- 2. Gutachter: Prof. Dr. Johannes Haller

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Zusammenfassung

Diese Arbeit stellt eine Suche nach neuer Physik vor, die die Streuung von elektroschwachen Bosonen ($VV \rightarrow VV$, wobei V ein W^{\pm} oder ein Z Boson bezeichnet) analysiert, welche in Assoziation mit zwei Jets in proton-proton-Kollisionen bei einer Schwerpunktsenergie von $\sqrt{s} = 13$ TeV produziert werden. Um das Verständnis des Mechanismus der elektroschwachen Symmetriebrechung zu erweitern, werden die Eichboson-Kopplungen präzise im Studium von Vektorboson-Streuung vermessen. [1] In dieser Analyse beschränken wir die anomalen quartischen Eichboson-Kopplungen durch Ausschlussgrenzen auf Parameter eines Framework von Dimension-Acht Operatoren einer effektiven Feldtheorie. Der Endzustand mit Jets wird bei invarianten Di-Boson Massen größer als 1 TeV erstmals untersucht. Die beiden Bosonen haben einen starken Lorentz-Boost und bilden jeweils einen einzelnen Jet mit Substruktur, was eine deutliche Reduzierung der Standardmodell-Untergründe ermöglicht.

Diese Analyse ermittelt die stringentesten Ausschlussgrenzen für 16 von 18 Dimension-Acht Operatoren.

Abstract

This thesis presents a search for new physics analysing the scattering of electroweak vector bosons ($VV \rightarrow VV$, where V denotes a W^{\pm} or a Z boson) produced in association with two jets in pp-collisions at $\sqrt{s} = 13$ TeV. The study of vector boson scattering can help to improve the understanding of the mechanism behind electroweak symmetry breaking, and to find new physics by precisely measuring gauge boson couplings. In this analysis we constrain the anomalous quartic gauge couplings in terms of a exclusion limits on parameters in a framework of dimension-eight effective field theory operators. The all-jets final state with di-boson invariant masses larger than 1 TeV is explored for the first time. The two bosons are highly boosted and each form a single jet with substructure, allowing for a significant reduction of SM backgrounds and thus improvement in analysis sensitivity.

This analysis sets the most stringent exclusion limits for 16 of 18 dimension-eight operators.

1 Introduction

In modern particle physics, the elementary particles and three out of four known fundamental forces are described by the theory of the standard model (SM).

With the discovery of the Higgs boson in 2012, and subsequent measurements of its couplings, another success of the SM has been reported and it was clarified why fermions and heavy gauge bosons are allowed to have a mass. [1, 2] Although it has been very successful so far, the SM has considerable weaknesses. One of the current problems of the SM is the fact that neither gravity as a fundamental force, nor the general theory of relativity, can be described uniformly with the SM, or rather all attempted explanation have not yet been proven. Also, dark matter and dark energy, whose existence is indicated by astrophysical observings, cannot be described by the current SM.

In the search for explanations for these open problems of the SM, large experiments are carried out in which particles are collided in order to test theories on the basis of the observed behavior of the particles. At the moment the Large Hadron Collider plays a major role because it is the largest and most powerful proton-proton collider to date. Due to its high center-of-mass energy of $\sqrt{s} = 13$ TeV, processes can be observed at the LHC that are very rare and thus decisive in the search for new physics and deviations from SM.

In this thesis vector boson scatterings are analysed to search for deviations in the mechanism of electroweak symmetry breaking. The Feynman diagram of such a vector boson scattering can be found in figure 1.1. Here we have two vector bosons which are produced in the fusion of two other vector bosons, in association with two quarks. This analysis differs from the



Figure 1.1: Feynman diagram of the vector boson scattering via (anomalous) electroweak quartic gauge coupling.

previously published analyses, because it is the first one to consider the all-jets final state, i.e. that both bosons decay hadronically. This results in a larger cross section than for the leptonic modes, which benefits the analysis; however on the other hand a (much larger) QCD background has to be dealt with. The analysis assumes a high invariant mass of the boson boson system, which in turn results in the bosons being highly Lorentz-boosted. The decay products of such a boosted boson will be very collimated, whereby they will be reconstructed

as a single fat jet with substructure. The vertex with four bosons introduces quartic gauge couplings into the process. By potential variations of these couplings due to physics beyond the standard model, the cross section of the process can be increased at high energies. Thus, changes in the tail of high-energy distributions would indicate *anomalous quartic gauge couplings*. In this thesis the invariant mass spectrum of the resulting fat jets is analysed. To model the deviations in the form of anomalous quartic gauge couplings, a framework of an *effective field theory* (EFT) is used for this analysis. This EFT extends the standard model Lagrangian by independently scaled operators, which change the couplings at quartic vertices. The aim of the analysis will be to calculate exclusion limits on a set of scaling parameters¹ of the EFT. This has already been done in numerous other published studies and table 1 shows the currently most stringent published limits on the set of aQGC-EFT parameters.

In the following chapter 2 the theoretical basics for the general understanding of the remaining thesis are explained. Then in chapter 3 the experimental setup, with the CMS detector and the LHC, as well as the reconstruction of its measurements, is explained. Chapter 4 explains how complete events are simulated with Monte-Carlo generators. Also the event selection is explained, which aims to enrich the signal and reject the background. In chapter 5 the main part of the analysis is explained. This includes the background estimation, closure tests in simulation and a data sideband regions, and the limit setting procedure. Chapter 6 presents the results of the calculation of the anomalous quartic gauge coupling limits, and finally chapter 7 discusses them, and explains potential improvements for the future.

¹This includes the parameter of the operators S_i , M_i and T_i .

aQGC parameter	literature limit [TeV ⁻¹]				
F _{S0}	(-7.7,7.7)	ssWW [3]			
F _{S1}	(-21.8,21.8)	ssWW [3]			
F _{M0}	(-4.2, 4.2)	$\gamma \gamma \rightarrow WW [4]$			
$F_{\rm M1}$	(-8.7,9.1)	ssWW [3]			
F _{M2}	(-26,26)	Wγ [5]			
$F_{\rm M3}$	(-43,44)	Wγ [5]			
F _{M4}	(-40,40	Wγ [5]			
F _{M5}	(-65,65)	Wγ [5]			
$F_{\rm M6}$	(-11.9,11.8)	ssWW [3]			
F _{M7}	(-13.3, 12.9)	ssWW [3]			
F _{T0}	(-0.46, 0.44)	ZZ [6]			
F_{T1}	(-0.28,0.31)	ssWW [3]			
F _{T2}	(-0.89, 1.02)	ssWW [3]			
F_{T5}	(-3.8, 3.8)	Wγ [5]			
F _{T6}	(-2.8, 3.0)	Wγ [5]			
F_{T7}	(-7.3, 7.7)	Wγ [5]			
F _{T8}	(-0.84, 0.84)	ZZ [6]			
F _{T9}	(-1.8, 1.8)	ZZ [6]			

Table 1: Overview of the current most stringent limits on the aQGC parameters from the analyses in [3–6]. The channel, that the respective analysis was performed in is listed in right column.

2 Theory

2.1 The Standard Model

The Standard Model (SM) of particle physics is the mathematical description of the known elementary particles and three of the four fundamental forces in the form of quantum field theories. The SM postulates a local gauge invariance of the corresponding Lagrangian under transformations of the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ symmetry groups. This leads to three different types of interactions between fermions (particles with half-integer spin) under the exchange of gauge bosons (integer spin). These interactions are known as the electromagnetic, weak and strong interactions.

The fermions form all observable matter and can be divided into six leptons and six quarks as seen in Figure 2.1. Additionally each particle has an anti-particle partner, which differs only in its physical charge. The leptons consist of the electrically neutral neutrinos (v_e, v_μ, v_τ) and the electrically charged leptons (e^-, μ^-, τ^-) $(Q = 1e \triangleq$ Charge of electron). All 6 quarks are electrically charged: the up-type quarks (u, c, t) carry a charge of $Q = \frac{2}{3}$ and the down-type quarks (d, s, b) a charge of $Q = \frac{1}{3}$. Furthermore, the up-type and down-type quarks are ordered into three generations by increasing mass.





The *electroweak unification* of the electromagnetic and weak interactions is described as part of the SM. The invariance of the Lagrangian under local phase transformation of the $SU(2)_L \otimes U(1)_Y$ leads to 3 + 1 gauge bosons: the three weak bosons W^1, W^2 , and W^3 , along with the *B*

boson. These bosons couple to particles which carry the charge of the respective symmetry group: the weak isospin I_W^3 of SU(2) and the electric charge Q of U(1). Combinations of these produce the experimentally observed W^{\pm}, Z^0 and γ bosons. Due to observed parity violation in the weak interaction the Lagrangian contains a *vector minus axial-vector* (V - A) structure. As a result of this the gauge bosons of the $SU(2)_L$ symmetry only couple to left-handed fermions and right-handed anti-fermions (hence the index L in $SU(2)_L$). The handedness refers to the chiral state of the particle. The chirality is closely related to the helicity $(\hat{\lambda} = \frac{\vec{S}\vec{p}}{|\vec{S}|\cdot|\vec{p}|},$ where \vec{S} and \vec{p} are the spin and momentum vector of a particle). For example in the ultra relativistic limit a particle with positive helicity is almost completely left-handed. The left-handed fermions are arranged in weak isospin doublets:

$$\begin{pmatrix} \mathbf{v}_e \\ e^- \end{pmatrix}_L, \quad \begin{pmatrix} \mathbf{v}_\mu \\ \mu^- \end{pmatrix}_L, \quad \begin{pmatrix} \mathbf{v}_\tau \\ \tau^- \end{pmatrix}_L, \quad \begin{pmatrix} u \\ d' \end{pmatrix}_L, \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L, \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L.$$
(2.1)

Here the fermions in the top row (the neutrinos and up-type quarks) carry a weak Isospin of $I_W^3 = \frac{1}{2}$, while the fermions on the bottom row carry $I_W^3 = -\frac{1}{2}$. The right-handed fermions are ordered as weak isospin singlets with $I_W^3 = 0$, which are unaffected by the local phase transformation:

$$e_{R}^{-}, v_{e,R}^{-}, \mu_{R}^{-}, v_{\mu,R}^{-}, \tau_{R}^{-}, v_{\tau,R}^{-}, u_{R}^{-}, c_{R}^{-}, t_{R}^{-}, d_{R}^{-}, s_{R}^{-}, b_{R}^{-}.$$
 (2.2)

In the isospin doublets one finds not the physical mass eigenstates but the weak eigenstates. The mass eigenstates are mixtures of the weak eigenstates. For example the weak eigenstates of the down-type quarks are related to the mass eigenstates through the CKM matrix (with values from [8]):

$$\begin{pmatrix} d'\\s'\\b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub}\\V_{cd} & V_{cs} & V_{cb}\\V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d\\s\\b \end{pmatrix} = \begin{pmatrix} 0.974 & 0.225 & 0.004\\0.224 & 0.974 & 0.042\\0.009 & 0.041 & 0.999 \end{pmatrix} \begin{pmatrix} d\\s\\b \end{pmatrix}.$$
(2.3)

This also introduces mixing between generations of quarks. The experimentally observed physical W^{\pm} bosons are obtained by linear combinations of the boson-fields W^{1}_{μ} and W^{2}_{μ} :

$$W^{\pm}_{\mu} = \frac{1}{\sqrt{2}} (W^{1}_{\mu} \mp W^{2}_{\mu})$$
(2.4)

As the electrically neutral Z^0 boson also couples to right-handed fermions it can not be identified with the W^3 boson alone. The gauge boson of the electromagnetic interaction, the photon γ and the Z^0 boson are both obtained by mixing the W^3 with the *B* boson of the

 $U(1)_{Y}$:

$$A_{\mu} = +B_{\mu}\cos\theta_{W} + W_{\mu}^{3}\sin\theta_{W}, \qquad (2.5)$$

$$Z_{\mu} = -B_{\mu}\sin\theta_W + W_{\mu}^3\cos\theta_W. \tag{2.6}$$

Here A_{μ} denotes the photon-field and θ_W is the mixing angle known as the *Weinberg angle*. Since the Z^0 is a combination of both the *B* and W^3 , it couples to the *hypercharge Y* (see Eq. 2.7) and thus to the isospin singlets.

$$Y = 2(Q - I_W^3)$$
(2.7)

While the photon is massless, the bosons of the weak interaction do have a mass. The masses $m_W = 80.4 \text{ GeV}/c^2$ and $m_Z = 91.2 \text{ GeV}/c^2$ [8] are also related to each other via the *Weinberg* angle :

$$\cos\theta_W = \frac{m_w}{m_Z}.$$
(2.8)

The strong interaction arises from gauge invariance under local phase transformations of $SU(3)_c$. The resulting eight massless gauge bosons are called *gluons*. They couple to particles with *color*-charge, which is either *red*, *blue*, or *green*. The eight gluons correspond to the eight linearly independent color states, and carry color-charge themselves:

$$|1\rangle = (r\bar{b} + b\bar{r})/\sqrt{2}$$
 $|5\rangle = -i(r\bar{g} - g\bar{r})/\sqrt{2}$ (2.9)

$$|2\rangle = -i(r\bar{b} - b\bar{r})/\sqrt{2}$$
 $|6\rangle = (b\bar{g} + g\bar{b})/\sqrt{2}$ (2.10)

$$|3\rangle = (r\bar{r} - r\bar{r})/\sqrt{2}$$
 $|7\rangle = -i(b\bar{g} - g\bar{b})/\sqrt{2}$ (2.11)

$$|4\rangle = (r\bar{g} + g\bar{r})/\sqrt{2} \qquad |8\rangle = (r\bar{r} + b\bar{b} - 2g\bar{g})/\sqrt{6}. \qquad (2.12)$$

Consequently the gluons mediate interactions between all colored particles, including other gluons. The only other particles that carry color-charge and thus interact strongly are the quarks. An aspect of QCD is *asymptotic freedom*, where the strong force increases with the distance between the interacting quarks. Therefore quarks in bound states or at very high energies, i.e. quarks that are close to one another or highly energetic, can be seen as quasi-free particles. If in bound states of quarks their distance is increased, they do not separate to single quarks due to the effect of *color confinement*. Since the gluons themselves carry color charge, the field lines between the quarks condense, resulting in an increase in potential with the distance. At a certain distance it is energetically more favorable to form further (anti)quarks and thus to form color-neutral quark-antiquark pairs. These "colorless states" consist of a combination of either color and anti-color, or of all three colors. This process of pair-production is also called *hadronization*. In detectors, high-energy quarks and gluons form so-called "*jets*". This happens through the process of hadronization and the formation of hadronic showers. The initial particles decay into cascades and the resulting particles

hadronize to colorless states and form the jets.

As the standard model Lagrangian would not be invariant with explicit mass terms for the massive gauge bosons and fermions, the *Brout-Englert-Higgs mechanism* is necessary [9] to generate masses for the particles. Here the complex scalar Higgs field doublet ϕ is introduced, which consequently leads to the spontaneous breaking of the electroweak symmetry. All massive particles interact with the Higgs field, and an excitation of it leads to another massive boson, the *Higgs boson*. It is a scalar spin-0 boson with an experimentally measured mass of $m_h = 125.18$ GeV [8].

The fourth observed force in nature is *gravity*. The current standard model is not equipped to explain its origin, instead it is described by general relativity in a separate theory.

A detailed explanation of the standard model can be found for example in [10], [11] and [12].



Figure 2.2: Cross section in nb (nanobarns) of the scattering processes of the weak gauge bosons. The left plot shows the standard model with a Higgs boson with a mass of 120 GeV. On the right a model of the standard model without a Higgs boson is shown. [13]

2.1.1 Vector Boson Scattering

To strengthen the understanding of the validity of the standard model, the study of rare processes that exploit the high energies of accelerators like the LHC is crucial in modern particle physics. One such process is vector boson scattering [14]. Here, two incoming (anti) quarks each emit a electroweak gauge boson (γ , W^{\pm} , or Z^{0}). These vector bosons interact (scatter) with each other, producing two outgoing bosons (as seen on the right in figure 2.2). The scattered quarks (or antiquarks) will each form a highly energetic jet, which is highly collimated with the direction of the incoming proton.

This thesis focuses on processes where the two produced bosons are W^{\pm} or Z^{0} bosons. Figure 2.2 shows the cross sections of different vector boson scattering processes, both with and without a Higgs boson. When a Higgs is present, and has the same properties as predicted in the SM, the cross section at high energies keeps decreasing. On the other hand when there is no Higgs there would be a strong increase of the cross section above 1 TeV. This motivates



Figure 2.3: Feynman diagrams of vector boson scattering with and without higgs boson.

analyses which probe the standard model in these TeV ranges for deviations in the mechanism of electroweak symmetry breaking. Recent results of the CMS and ATLAS Collaborations show the first observation of the production of same-sign *W* boson pairs at the LHC ([3], [15]). With this confirmation of quartic gauge boson vertices, the next step in analyses of vector boson scattering processes is the search for anomalies in these couplings, or non-resonant contributions from new physics. Both would increase the cross-section at high energies as mentioned above.

In Figure 2.4 this has been illustrated on the right for the invariant mass of the diboson system in the VBS final state.

In this thesis we look for the all-jets final state from vector boson scattering, where both vector bosons decay to hadronic final states. Besides the two forward jets that are produced in association with the vector boson fusion there will also be jets from the hadronic decay of the vector bosons ($V_f \rightarrow jj$). Since possible deviations are largest at higher diboson masses we focus there with $m_{VV} \gtrsim 1$ TeV. Thus the transverse momentum p_T of the bosons is large, whereby highly collimated decay products are produced with the decay of the bosons. These will be reconstructed as single "fat" jets. Consequently there are four jets in the final state of the analysed processes as shown on the left in figure 2.4.

2.2 Beyond Standard Model

Despite its success in describing many aspects of modern particle physics, the SM is not perfect. Various inconsistencies are observed in experiments, and are the focus of current research to extend our understanding of fundamental physics.

As mentioned before there is satisfactory theory that combines *gravity* and *general relativity* in the standard model. Thus a popular goal in modern physics is a **G**rand **U**nified Theory, that unifies the 3 known fundamental forces with gravity.

Another problem with the standard model is the absence of dark matter candidates. From observations of the rotation of spiral galaxies we known that something like dark matter and dark energy are making up for $\sim 27\%$ and $\sim 68\%$ of our Universe, respectively [16]. Various



Figure 2.4: In the right Figure the Diboson-Mass of SM background (blue) and BSM signal (red) is outlined. On the left a schematic drawing of the given jet topology is shown.

theories extending the standard model, like *Supersymmetry* (SUSY), are introducing different particles as such candidates.

In this thesis, we do not focus on one specific **B**eyond the **S**tandard **M**odel theory. Instead we perform a model-independent search.

2.2.1 Effective Field Theory

One possible model independent description of new physics is an effective field theory. A standard model-extending effective field theory (*SMEFT*) framework is used to model the BSM contributions in the form of anomalous quartic gauge couplings [17]. The standard model Lagrangian is therefore extended by a number of independently-scaled operators of different mass dimensions:

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \mathscr{L}^5 + \mathscr{L}^6 + \mathscr{L}^7 + \mathscr{L}^8 + \cdots, \qquad (2.13)$$

where \mathscr{L}_{SM} is the SM Lagrangian, and $\mathscr{L}^{(k)}$ is a linear combination of n_k dimension-k operators, $\mathscr{O}_i^{(k)}$:

$$\mathcal{L}^{(k)} = \sum_{i=1}^{n_k} F_i^{(k)} \mathcal{O}_i^{(k)} \text{ for } k > 4, \qquad (2.14)$$

where $F_i^{(k)}$ are free mixing coefficients, which can be parametrized in the form:

$$F_i^{(k)} = \frac{C_i^{(k)}}{\Lambda^{k-4}},\tag{2.15}$$

where Λ is the scale at which new physics is expected. The lowest dimension operators to get exclusively quartic vertices (like the one in figure 2.5) are operators of dimension-eight. We



Figure 2.5: Example of a Feynman diagram of the vector boson scattering of W^+ bosons via anomalous quartic gauge couplings.

therefore focus on these dimension-eight operators, since higher dimension operators will have smaller contributions. In Table 2 these dimension-eight parameters of these operators are shown, indicating to which vertices each operator contributes. As the analysis in this thesis focuses on W^{\pm} and Z^{0} bosons in the final state of the vector boson scattering. we consider all operators that contribute at least two of the desired W^{\pm} and Z bosons. This applies to all 18 listed operators.

Parameter of dim8 Operator	wwww	WWZZ	ZZZZ	WWγZ	WWγγ	ZZZγ	ΖΖγγ	Ζγγγ	үүүү
F_{S0}, F_{S1}	Х	Х	Х						
$F_{M0}, F_{M1}, F_{M6}, F_{M7}$	Х	Х	Х	Х	Х	X	Х		
$F_{M2}, F_{M3}, F_{M4}, F_{M5}$		Х	Х	Х	Х	X	Х		
F_{T0}, F_{T1}, F_{T2}	Х	Х	Х	Х	Х	X	X	X	Х
F_{T5}, F_{T6}, F_{T7}		X	Х	Х	Х	X	Х	X	Х
F_{T8}, F_{T9}			Х			X	X	X	Х

Table 2: Overview of the scaling parameters for the SMEFT operators of dimension-eight. "X" denotes a vertex the respective operator contributes to.

The operators consist of various combinations of covariant derivatives of the Higgs doublet and the field strength tensors of the SU(2) and U(1). They can be divided into three categories, where they contain either only covariant derivatives of the Higgs doublet (S_i operators), contain both covariant derivatives of the Higgs doublet and field strength tensors (M_i operators), or containing only field strength tensors (T_i operators).

$$\mathcal{O}_{S0} = [(D_{\mu}\Phi)^{\dagger}D_{\nu}\Phi] \times [(D^{\mu}\Phi)^{\dagger}D^{\nu}\Phi]$$

$$\mathcal{O}_{S1} = [(D_{\mu}\Phi)^{\dagger}D^{\mu}\Phi] \times [(D_{\nu}\Phi)^{\dagger}D^{\nu}\Phi]$$
(2.16)

$$\begin{aligned} \mathcal{O}_{M0} &= \operatorname{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times [(D_{\beta}\Phi)^{\dagger}D^{\beta}\Phi] & \mathcal{O}_{T0} &= \operatorname{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times \operatorname{Tr}[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}] \\ \mathcal{O}_{M1} &= \operatorname{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\beta}] \times [(D_{\beta}\Phi)^{\dagger}D^{\mu}\Phi] & \mathcal{O}_{T1} &= \operatorname{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \operatorname{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}] \\ \mathcal{O}_{M2} &= [B_{\mu\nu}B^{\mu\nu}] \times [(D_{\beta}\Phi)^{\dagger}D^{\beta}\Phi] & \mathcal{O}_{T2} &= \operatorname{Tr}[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}] \times \operatorname{Tr}[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}] \\ \mathcal{O}_{M3} &= [B_{\mu\nu}B^{\nu\beta}] \times [(D_{\beta}\Phi)^{\dagger}D^{\mu}\Phi] & \mathcal{O}_{T5} &= \operatorname{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times B_{\alpha\beta}B^{\alpha\beta} \\ \mathcal{O}_{M4} &= [(D_{\mu}\Phi)^{\dagger}\hat{W}_{\beta\nu}D^{\mu}\Phi] \times B^{\beta\nu} & \mathcal{O}_{T6} &= \operatorname{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times B_{\mu\beta}B^{\alpha\nu} \\ \mathcal{O}_{M5} &= [(D_{\mu}\Phi)^{\dagger}\hat{W}_{\beta\nu}D^{\nu}\Phi] \times B^{\beta\mu} + \operatorname{h.c.} & \mathcal{O}_{T7} &= \operatorname{Tr}[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}] \times B_{\beta\nu}B^{\nu\alpha} \\ \mathcal{O}_{M6} &= [(D_{\mu}\Phi)^{\dagger}\hat{W}_{\beta\nu}\hat{W}^{\beta\nu}D^{\mu}\Phi] & \mathcal{O}_{T8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\ \mathcal{O}_{M7} &= [(D_{\mu}\Phi)^{\dagger}\hat{W}_{\beta\nu}\hat{W}^{\beta\mu}D^{\nu}\Phi] & \mathcal{O}_{T9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \\ \end{aligned}$$

$$(2.17) & (2.18)$$

Here the weak field strength tensor is embedded in

$$\hat{W}_{\mu\nu} = \sum_{j} W^{j}_{\mu\nu} \frac{\sigma^{j}}{2}.$$
(2.19)

2.3 Backgrounds

The obvious standard model background of the analysed process is from the electroweak diboson production. Due to the identical signature, this process cannot be reduced (irreducible), but has a negligibly small effective cross section compared to other background processes in the all-jets final state.

Two additional reducible backgrounds are $t\bar{t}$ and $V \rightarrow qq$ + jets. Both can end up with 4 jets in the final state. The main reducible background comes from QCD multijet production. These processes, which are very similar to the final state signature of the signal, are produced via matrix elements of quantum chromodynamics.



Figure 2.6: Examples for Feynman diagrams of the four standard model backgrounds. On the top left the standard model vector boson scattering process is shown. On the top right is an example for V + jets where the boson decays into two quarks. On the bottom left the $t\bar{t}$ and on the bottom right QCD multijet process is shown.

3 Experimental Setup and Methods

3.1 Large Hadron Collider

The Large Hadron Collider (LHC) is, with its circumference of 26.7 km, the worlds largest circular proton-proton collider [18]. Build by the **C**onseil Européen pour la **R**echerche **N**ucléaire (CERN) near Geneva in Switzerland, it can deliver collisions of protons at a center of mass energy up to $\sqrt{s} = 13$ TeV and a instantaneous luminosity of the order $\mathscr{L} \approx 10^{34}$ cm⁻¹s⁻¹. The collisions are recorded at each one of the four collision points by the following experiments: **A** Large Ion Collider Experiment (ALICE), **A** Torodial LHC **A**pparatus (ATLAS), **C**ompact **M**uon **S**olenoid (CMS), and Large Hadron Collider **b**eauty (LHCb). While both ATLAS and CMS analyse proton-proton and heavy Ion collisions for SM and BSM phenomena, LHCb specializes in B-Meson physics, and ALICE explores heavy ion collisions.

The LHC itself is the last accelerator in a series of accelerators. In 4 pre-accelerators the protons are accelerated to an energy of approximately 450 GeV. The main ring of the LHC consist of eight straight and eight curved sections. Two proton beams are steered by dipole magnets through the curved sections. The functions of the straight sections include the acceleration by RF cavities, injection from the pre-accelerators, focusing and other beam manipulation by multipole magnets. The two beams travel in opposite directions through separate channels within the ring, with a revolution frequency of f = 11.25 kHz. Both beams consist of proton bunches with a spacing of 25 ns between each other leading to k = 2808 bunches per beam. There are roughly $n \approx 1.1 \times 10^{11}$ protons in each of these bunches. [19]

In order to quantify the amount of beam collisions the instantaneous luminosity $\mathcal L$ is used:

$$\mathscr{L} = \frac{dN}{dt} \cdot \frac{1}{\sigma_p} = \frac{kn^2 f}{4\pi\sigma_x \sigma_v} F.$$
(3.1)

Here σ_x and σ_y are the vertical and horizontal beam sizes, which are almost identical Gaussian profiles at the interaction points. $F(\leq 1)$ is a correction parameter, that takes into account that the bunches cross each other at an angle at the interaction point. With the relation of the instantaneous luminosity to the event rate $\frac{dN}{dt}$ and the cross-section of the pp-collisions σ_p the number of expected data events N can be calculated with the time-integrated luminosity:

$$N = \sigma_p \cdot \int \mathscr{L} dt. \tag{3.2}$$

The analysis of this thesis uses a set of data recorded in 2016 with the CMS Detector. This dataset includes a total integrated luminosity of $\mathcal{L}_{int} = 35.9 \text{ fb}^{-1}$ [20].



3.2 The Compact Muon Solenoid Detector

Figure 3.1: Detailed overview of the CMS-Detector [21]

One of the four large particle detectors at the LHC, the Compact Muon Solenoid is a multipurpose particle detector. In its overall design (seen in Fig. 3.1) there is a focus on the measurement of the momentum of muons. In the heart of the detector one finds the inner tracking system, surrounded by an electromagnetic and subsequently a hadronic calorimeter. Around all these sub-detectors sits a superconducting solenoid, which generates a strong magnetic field of 3.8 T. The detector is enclosed by muon detectors, which are traversed with an iron yoke to return the magnetic field. With two additional calorimeters to cover the forward region near the proton beampipe, the detector measures 21.6 m in length, 14.6 m in diameter, and has a weight of 12500 t [22]. In the CMS detector a right-handed coordinate system is used. It has its origin at the proton-proton interaction point. While the *x*-axis points radially towards the center of the LHC ring, the *y*-axis points upwards and the *z*-axis is parallel to the beam pipe. The polar angle θ is measured from the *z*-axis and the azimuthal angle ϕ is measured from the *x*-axis in the *x*-*y* plane [23]. As differences in the polar angle θ are not Lorentz invariant, the pseudorapidity η is used instead:

$$\eta = -\ln \tan \frac{\theta}{2}.\tag{3.3}$$

Differences in pseudorapidity are Lorentz invariant. Furthermore, the transverse momentum p_T (and energy E_T) is calculated in the *x*-*y* plane using the *x*- and *y*-components of the momentum: $p_T = \sqrt{p_x^2 + p_y^2}$.



Figure 3.2: Overview of the tracking system of the CMS-Detector with its strip tracker and pixel tracker [23].

3.2.1 Tracker System

The Tracker system consist of the pixel tracker and the strip tracker. Together the two components cover the region up to $|\eta| < 2.4$. As the tracker system is the innermost component of CMS it receives the highest particle flux and therefore has to be made out of radiation-hard material, as well as being very fast at processing a large number of input signals.

The **pixel detector** consists of three layers of silicon sensors located in a "barrel" format around the beam pipe at different radii, the smallest being 4.4 cm. Additionally there is a disk with pixels at each endcap of the barrel. Altogether there are 66 million pixels with dimension $100 \times 150 \ \mu m^2$. After the 2016 data taking the pixel detector was upgraded with a four-layer system.

The **strip detector** starts at a distance to the beam pipe of 20 cm. It includes, similarly to the pixel detector, separate barrel and endcap sections. The *Tracker Inner Barrel* (TIB) and *Tracker Outer Barrel* (TOB) in the barrel, and the *Tracker Inner Disks* (TID) and *Tracker End Cap* (TEC) in the endcaps, are located around the pixel detector as seen in Figure 3.2. They all consist of layers of silicon strip sensors. The inner layers have a strip thickness of 320 μ m with a pitch that varies between 80 to 120 μ m. In the outer layers, they are sufficiently far away from the beam pipe such that the particle flux is smaller. Thus a larger strip thickness of 500 μ m can be used to obtain better signal to noise ratio, while also using longer strips and larger pitches in the range of 120 to 180 μ m.

The tracking system is used to reconstruct the trajectory of charged particles, which will be curved due to traversing the magnetic field. These trajectories will have a curvature that depends on their electrical charge, momentum, and the strength of the magnetic field B. Measuring the radius of curvature R one can then calculate the momentum of the particle:

$$p \propto R \cdot B$$
 (3.4)

3.2.2 Calorimeter

Outside of the tracking system there are the two calorimeters. They are used to measure the energy of the particles. When a particle enters a calorimeter it interacts, causing a cascade and ultimately generating a shower of particles. The scintillating material of the calorimeter is excited by the particles and emits photons when returning from the excited to the ground state. The photons are then used to deduce the energy of the original particle, since the energy is proportional to cumulative intensity of the emitted photons. The two calorimeters of CMS were designed to be sensitive to specific particles: the electromagnetic calorimeter (ECAL) for electromagnetically interacting particles, and the hadronic calorimeter (HCAL) for strongly interacting particles.

Electromagnetic Calorimeter

The electromagnetic calorimeter is responsible for the measurement of the energy of the electromagnetically interacting photon and electron. It is constructed with scintillating crystals made of lead-tungstate(PbWO₄), which acts both as the absorber and the active element (a "homogeneous" calorimeter). Lead-tungstate has a radiation length of $X_0 = 0.89$ cm. The radiation length indicates the mean length that a photon or electron needs to traverse to lose $\frac{1}{e}$ of its energy due to e^+e^- pair production or bremsstrahlung respectively. Both effects together lead to *electromagnetic showers*.

Similar to the tracker system the electromagnetic calorimeter consists of separate barrel and endcap parts. The *barrel calorimeter* is constructed with 621400 lead-tungstate crystals. Each of those crystal is 22 mm in width and height at their front face, and 26 mm in height and width at their rear face [23]. The small radiation length is one reason that it was possible to achieve a compact design with a crystal length of 230 mm (25.8 X_0). The two *endcap calorimeters* increase the a total coverage of the ECAL up to $|\eta| < 3.0$. In each endcap are 7324 identical crystals. They are 28.62 mm in width and height at their front face, 30 mm in width and height at their rear face, and 220 mm long (24.7 X_0) [22]. Before particles enter the endcap calorimeters they pass an additional *preshower device*, which aims to identify neutral pions that decay into a low-energy photon pairs.

Hadronic Calorimeter

The hadronic calorimeter is used for the energy measurement of charged and neutral hadrons. Unlike the ECAL the hadronic calorimeter is not a homogeneous calorimeter, but rather a sampling calorimeter, meaning that absorber and active element are not the same material. This is necessary because the characteristic interaction length λ_I of the hadrons is larger than of their electromagnetic counterpart X_0 . Sampling calorimeters therefore consist of alternating absorber and active elements to ensure that the entire particle's shower is captured inside the calorimeter. The negative effect on the energy resolution due to the energy loss in the absorber is countered by the gained granularity of the calorimeter due to the longitudinally

segmented design.

The HCAL is composed of the **HB**arrel, **HO**uter, **HE**ndcap and **HF**orward. The absorber material for the HB and HE is brass, and for the HO and HF it is steel. For the HB, HO and HE plastic scintillator is the active element. They are equipped with wavelength shifting fibres that collect the emitted light. In contrast, the HF uses quartz fibres, which utilizes Cherenkov light. The HO is placed after the solenoid to catch particles that have passed through both the HB and the magnet [23].

Together the HB and HE cover the region up to $|\eta| < 3.0$, while the HO covers the region up to $|\eta| < 1.26$ [22]. The HF is used to measure forwards objects in the region $3.0 < |\eta| < 5.0$.

3.2.3 Solenoid

As mentioned before, a magnetic field is used to bend the trajectories of charged particles in order to measure their momentum and identify their charge and type. CMS uses a superconducting solenoid that was designed to generate a magnetic field up to 3.8 T [22]. With its length of 12.9 m and a inner diameter of 5.8 m it can fit the majority of the sub-detectors inside. An iron yoke is used to return the magnetic field through the muon system. The resulting magnetic field in the muon system is in opposite direction and improves the measurement of the muons momentum.

3.2.4 Muon System

The last sub-detector is the muon system. As muons in the LHC are generally minimally ionizing particles that will pass through the ECAL and HCAL, its main goal is the detection and measurement of the muons. It consist of a combination of gaseous detectors: *Resistive Plate Chambers* (RPC), *Cathode Strip Chambers* (CSC), and *Drift Tube* (DT) *Chambers*. The fast RPCs are used in all parts of the muon system to improve the time resolution of measurements and aid the trigger system. The muon system also consists of barrel and endcap parts. In the barrel part the DTs are used, while in the endcaps CSCs are deployed. Altogether the muon system offers coverage up to $|\eta| < 2.4$ [22].

3.2.5 Trigger

With a bunch crossing happening every 25 ns the LHC produces roughly 10⁹ collisions per second. Due to technical limitations only 10² of these crossing can be recorded per second which introduces the necessity of the trigger system to only keep data from "interesting" events. The trigger system used at CMS includes the *Level-1* trigger which is hardware-based, and the software-based *High-Level Triggers*.

In the first step the hardware logic of the L1 Trigger decides in 3.2 μ s if a crossing is kept or discarded. Trigger objects like photons, electrons, muons and jets are formed from information delivered by the calorimeters and the muon system, but with reduced granularity and

resolutions . The presence of such trigger objects with a certain threshold on p_T or E_T , along with thresholds on the global scalar sum of transverse energy (E_T) , and magnitude of vector sum of transverse momentum $(\not\!\!E_T)$, are key elements in the decisions of the L1 Trigger. While the decision is being made the unprocessed data is held in pipelined storage, and after the latency of 3.2 μ s it is either discarded or passed to the HLT.

Here the event is (partly) reconstructed and rejected as soon as possible. Therefore first the information from the calorimeters and muon system is used, before also combining with data from the tracking system. Ultimately all parts of the detector are taken into account. The HLT reduces the rate of events from the 100 kHz output by the L1 trigger to order of 100 Hz [22].

3.3 Particle-Flow Algorithm

Having passed the trigger system, the raw data has to be processed to identify and reconstruct the physical objects. In CMS the particle-flow (PF) algorithm is used, which is explained in detail in [24]. The PF algorithm combines detailed information from all sub-detectors to reconstruct particles, utilizing the fact that each type of particle leaves specific signatures in various parts of the detector when traversing it (see Figure 3.3).

First, the information from the sub-detectors is processed independently, and tracks of charged particles, energy clusters and muon tracks are formed. The tracks and energy clusters are then combined, before the type of the particles is determined in the last step of the PF algorithm.

The track reconstruction happens iteratively with information from the tracking and muon system. In the first iteration single hits are combined under very stringent criteria to reconstruct tracks. For the next iterations, all hits that form the tracks from the previous step are then removed, and the procedure is repeated with less strict criteria.

Energy clusters are formed from each calorimeter. Calorimeter cells with a local energy maxima are first used as cluster seeds. Then adjacent cells with a certain energy threshold (dependent on the respective calorimeter noise level) are merged with the seed to form topological clusters.

In the second step of the PF algorithm all tracks and clusters are linked to each other to form so-called *blocks*. Tracks are extrapolated towards the calorimeters up to either the expected shower maximum in the ECAL or to the typical hadronic shower depth of one interaction length (λ_I). The extrapolated track is then linked to a cluster if it traverses inside the respective cluster boundaries. To account for electron's bremsstrahlung in the tracker, which produces photons in the ECAL, combinations between tangents of tracks and clusters in the ECAL are also included. Links between clusters from different calorimeters are also added. To quantify the quality of the combinations, the distance of the respective elements in the η - ϕ plane is used. The combination of tracks from the tracking system and muon system conclude the second step of the PF algorithm. Here combinations of two tracks that return an acceptable



Figure 3.3: Schematic drawing of a vertical slice of the CMS-Detector with specific signatures left by various types of particles. [25]

 χ^2 in a global fit are called *global muon*. The χ^2 also serves as the qualifying quantity of the combination block.

In the last PF step particles are reconstructed and identified from each block. The process starts with identifying *particle-flow muons* as global muons whose momentum agrees with the momentum calculated from the tracking system within three standard deviations. The tracks corresponding to particle-flow muons are then removed. Next electrons are considered. Accounting for the energy loss due to bremsstrahlung in the tracking system, *particle-flow electrons* are identified. After removing the corresponding tracks and clusters the remaining tracks are removed if the uncertainty on their measured momentum exceeds the calorimeter resolution for charged hadrons. Next the energies of calorimeter clusters and tracks are compared. If the energy in the calorimeter exceeds the value calculated from the track additional *particle-flow photons* and *particle-flow neutral hadrons* are identified with the excess energy. Conversely, if the cluster energy is exceeded by the track momentum, additional muons are searched for with loosened criteria. Blocks with compatible energies are considered *particle-flow charged hadrons*.

All remaining clusters are considered to originate from neutral hadrons and photons. While photons are expected to shower exclusively in the ECAL, the neutral hadrons primarily shower in the HCAL.

3.4 Jets

As discussed above due to the effect of hadronization the quarks produced in the hadron collisions do not form single hadrons but hadronic particle showers called *jets*. For the



Figure 3.4: Schematic example of jet clustering in anti- k_t algorithm with a jet radius parameter R = 1 [26].

reconstruction of the jets specific jet clustering algorithms are used. In this analysis the *anti*- k_t algorithm is used [26].

This sequential recombination algorithm analyses all particle-flow objects. For each possible particle combination (i, j) the following distance measure between them, d_{ij} , is calculated:

$$d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{\Delta R_{ij}^2}{R^2}.$$
(3.5)

Here the spatial separation is defined as $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ using the rapidity $y_{i,j}$ and the azimuthal angle $\phi_{i,j}$. d_{ij} is weighted with the larger of the two transverse momenta p_T . The parameter *R* introduces the radius parameter of the resulting jets. Additionally the distance measure of each particle to the beam is calculated:

$$d_{iB} = p_{T,i}^{-2}. (3.6)$$

Next all calculated values are compared. If the smallest value is a distance d_{ij} between the particle pair (ij), then this pair is merged into a new particle, and the next iteration of the algorithm is started with the updated list of particles. However if a distance between a particle *i* and the beam d_{iB} is the smallest, then this particle is considered a jet. The jet is removed from the particle list and another iteration of the algorithm begins. Once no particles are left in the list the algorithm stops with a completed list of jets. The algorithm first identifies the hard particles as jet seeds and adds the soft particles to it resulting in jets as seen in Figure 3.4. As an infrared and collinear safe jet clustering algorithm, the result of the anti- k_T algorithm is not influenced by the radiation of low-energy particles, or the collinear splitting of hard partons.

The jets used in the analysis of this thesis are processed with the *Pileup Per Particle Identification* (PUPPI) [27] method to mitigate the effect of pileup interactions, that arises from other protonproton collisions from the same or other bunch crossings. In the PUPPI mitigation technique a shape α is defined for each particle in the event to distinguish whether it comes from radiation from the leading vertex or from pileup-like radiation. Assuming that charged pileup has the same shape as neutral pileup, a weight for each particle can be determined by comparing the shape with the mean value of the distribution of the charged pileup. The weights range from 0 (pileup particle) to 1 (leading vertex). Finally, the particles are reweighted and only particles with a very small weight are discarded.

Furthermore, the jets have to meet additional quality criteria that reject signatures from detector noise [28].

Jets in the region up to $|\eta| \le 2.7$ have to satisfy:

- have at least one constituent,
- have the fraction of energy from neutral hadrons be < 0.99,
- have the fraction of energy from neutral electromagnetic particles be < 0.99.

Additionally for jets within $|\eta| < 2.4$,:

- have the fraction of energy from charged hadrons be < 0.99,
- the number of charged particles in the jet has to be > 0.

No criteria for $|\eta| > 2.7$ are applied. Additional jet energy corrections are applied according to recommendations from [29].

As explained in Section 2.1.1 the signal process has four jets in its final state. The two jets associated with the vector boson fusion (*VBF-jets*) are located in the forward η region and will be reconstructed with a jet radius of R = 0.4 ("AK4"). The other two jets result from the hadronic decay of the two produced vector bosons. As mentioned above the bosons in this analysis will be highly Lorentz-boosted. Thus the quarks from the boson decay will be highly collimated, and the decay of each boson will form a single "fat" jet. They will be reconstructed as jets with a radius of R = 0.8, i.e. AK8 jets. For the identification of AK8 jets from vector boson decays, a combination of requirements on jet-substructure variables is also used (*V-tagging*).

3.4.1 Jet-Substructure Variables

The jet-substructure variables used in this analysis are the mass of the jet, that is expected to correspond to the vector boson mass (softdrop mass), and an observable that quantifies the compatibility of the jet shape with a two-body decay (N-subjettiness).

Softdrop Mass

The identification of the jets resulting from the boosted boson decay is made more difficult



Figure 3.5: On the left: Comparison of masses before and after the softdrop procedure is applied to simulated events (taken from [30]), and on the right: Distribution of τ_2/τ_1 of jets originating from boosted *W* bosons (magenta) and QCD processes (blue) after certain requirement on the dijet and jet mass (taken from [31]).

due to contamination with wide-angle soft gluon and quark radiation that are included by the clustering algorithm with the large radius for AK8 jets. The softdrop algorithm [32] removes this soft radiation from the jets (*grooming*). Here first a jet j is reclustered with the Cambridge-Aachen (C/A) algorithm [33, 34] before it is declustered by the reversal of the last stage of clustering into two subjets j_1 and j_2 . Next the softdrop condition is calculated:

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}.$$
(3.7)

Here p_{Ti} is the transverse momentum of the *i*-th subjet, R_0 is the original jet radius and ΔR_{12} is the distance between the subjets in the $(y - \phi)$ plane as defined for the anti- k_t algorithm. The softdrop threshold z_{cut} and the angular exponent β control the intensity of jet grooming. If the condition is not met the procedure is repeated, using the subjet that has the larger transverse momentum, as the new jet. Once the subjets meet the condition the jet *j* is considered the final softdrop jet.

Crucially, for a jet from vector boson decay, the resulting softdrop mass of the jet tends towards the mass of the boson, whilst for QCD jets it will tend towards zero. CMS uses the threshold $z_{\text{cut}} = 0.1$ and $\beta = 0$.

N-subjettiness

The N-subjettiness measures how many subjets a jet consist of. When a boosted particle decays, nearly all of the decay products end up as constituents in a fat jet. Due to differences in the energy flow inside the jet, one can identify multiple regions with higher energy. The N-Subjettiness τ_N is an inclusive jet shape that describes how well the radiation in the jet is aligned with the *N* subjet candidates of a *N*-subjet hypothesis [31]. To get the N-Subjettiness

first one must identify N candidate subjets, by reclustering the jet with the Cambridge-Aachen (C/A) algorithm [33,34] and undoing the last N clustering steps. Then the N-Subjettiness τ_N is calculated using

$$\tau_{N} = \frac{1}{\sum_{k} p_{T,k} R_{0}} \sum_{k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\},$$
(3.8)

where $p_{T,k}$ is the transverse momentum of the *k*-th constituent, $\Delta R_{i,k}$ is the the distance in the $(\eta - \phi)$ plane between subjet *i* and constituent *k* and R_0 the original jet radius. If τ_n is near zero the jet has at most *N* subjets. If $\tau_N >> 0$ then the jet has energy away from the subjets, and thus consists of at least N + 1 subjets. Figure 3.5 shows on the right the N-Subjettiness ratio τ_2/τ_1 for *W*-jets and *QCD*-jets. Jets with $\tau_2/\tau_1 \approx 0$ are more likely to have two subjets rather than one.

4 Simulation and Event Selection

In modern particle physics simulations are used to understand the quality of the recorded data and to verify background estimates. These simulations are produced in a series of stages. The particular tools used in each step are discussed in this chapter. The simulation of complete events is more complicated for pp-collisions than, for example, for e^+e^- -collisions as the proton is a composite particle. The inner structure of the protons includes the three valence quarks ($u \ u \ d$), sea quarks, and gluons. The sea-quarks exist as quark-antiquark pairs, which result from gluon radiation in vacuum polarization. The constituents of the proton are called *partons* and carry a fraction of the protons momentum. These partons are the interacting particles in pp-collisions.

In scattering processes the momentum fraction of each of the partons is given by the Lorentzinvariant Bjorken x:

$$x = \frac{Q^2}{2 \cdot p \cdot q},\tag{4.1}$$

with the protons momentum p and the momentum transfer $Q^2 = -q^2$ [11]. The distribution of the momentum among the partons is described by the *Parton Distribution Function* (PDF) $f_i(x,Q^2)$ [35]. The calculation of the PDFs are extensive and different groups pursue various approaches to offer the best PDF for different situations. For the simulation of the signal processes in this thesis the PDF set of the NNPDF (Neural Network PDF) Collaboration for the LHC Run II [36] is used. Figure 4.1 shows the NNPDF 3.0 PDF for each flavor of proton constituent. Here one can see that the valence quarks are prevalent at high momentum fractions while sea quarks are found primarily at low momentum fractions. The cross-section of one interaction in a pp-collision to a final state a can be factorised out in terms of the matrix element of the hard parton interaction $\hat{\sigma}_{ij \to a}$ and the process-independent parton distribution functions of the partons $f_i(x; Q^2)$ and $f_i(x'; Q^2)$ [38].

$$\sigma_{pp' \to a} = \sum_{i,j} \int f_i(x; Q^2) \hat{\sigma}_{ij \to a} f_j(x'; Q^2) dx dx', \qquad (4.2)$$

Figure 4.2 shows a sketch of a event with the stages that are taken into account during the event simulation. A parton from each of the protons is selected to take part in the hard process, $ij \rightarrow a$ (red blob). Particles in both the initial- and final-states may radiate particles denoted initial- (ISR) and final-state radiation (FSR). The outgoing particles in the hard process, along with ISR/FSR partons, then undergo a parton shower, in which additional partons are radiated, e.g. $g \rightarrow qq$. These showers of partons are then hadronised, forming colorless hadrons that will decay or interact with the detector. The remaining parts of each incoming proton will also interact, forming the underlying event (purple blob). Multiple simultaneous *pp*-collisions may also occur, so-called *pileup*.



Figure 4.1: Parton Distribution Function for a momentum transfer $\mu^2 = 10 \text{ GeV}^2$. Generated with the NNPDF 3.0 PDF at NNLO - taken from [37]. Here u_V and d_v are the up and down valence quarks, respectively. Other quark flavors are sea quarks, with same distribution for both quark and antiquark for a given flavor



Figure 4.2: Overview of a collision with the stages that have to be handled in the event generation in different colors. Taken from [39].

4.1 Monte-Carlo Generator

The production of simulated samples begins with the Monte-Carlo (MC) generator. Here Monte-Carlo methods are used, i.e. the generation of random number distributions to solve problems numerically.

For the simulation of a process, the generator needs a theory model (e.g. the standard model) that provides the Lagrangian, couplings, and particle masses. With the Lagrangian of the theory model the generator can calculate all relevant Feynman diagrams for the process, and derive the respective matrix elements. With these, the generator is able to compute the amplitude of the process for a specific phase space. To do this the phase space is sampled for each event. A uniform distribution of random numbers is mapped onto the phase space variables. This can be repeated many times to reach the desired number of simulated events. Depending on how many vertices one adds to the process, more complex Feynman diagrams may be possible, and thus one refers to Monte-Carlo samples of *Leading Order* (LO), *Next to Leading Order* (NLO), NNLO, etc. The LO diagrams (also called Tree-Level) have the minimal number of vertices to produce the desired process. [40–42]

For the generation of the hard subprocess for the samples in this thesis, one of the following Monte-Carlo generator codes were used: MADGRAPH5_AMC@NLO [42], POWHEG [43–45] and PYTHIA8 [46]. The MADGRAPH5_AMC@NLO generator codes consists of the tree-level generator MADGRAPH and the AMC@NLO generator for NLO [47]. In this thesis MADGRAPH5_AMC@NLO was used to produce samples at LO. Additionally MADSPIN [48] was used to handle the decay of the final states that were generated by MADGRAPH.

While POWHEG produces samples at NLO, the generator Pythia8 can only operate at LO. Unlike the other generators, Pythia8 is a general-purpose MC generator that not only generates the hard signal, but also handles parton showering, hadronization and handling of the proton remnant to fully simulate a *pp*-collision. While LO in Pythia8 means that only tree-level processes are generated, MADGRAPH produces additional final state partons (without extra loops).

4.1.1 Parton Shower and Hadronization

After the generation of the hard subprocess the parton showers and hadronization processes have to be simulated. In this thesis Pythia8 is used to perform the parton showering in combination with the aforementioned hard process generators. To simulate hadronization, Pythia8 uses the empirical Lund-String model [49]. Here the QCD field between the quark antiquark pairs is modeled by a massless relativistic string that breaks when the energy exceeds a threshold. If the generator of the hard subprocess already generated additional partons it is important to match these to the parton showers produced in this step to avoid double counting of particles. The matching process depends on the choice of generator for each step. For the combination of MADGRAPH +Pythia8 the *MLM* technique [50] is used for the matching scheme as described in [51].

4.1.2 Detector simulation

The simulation of the behavior of particles as they traverse the detector is the last step in the simulation of events. Here GEANT4 is used [52] configured with a complete digital model of the CMS detector. The simulation accounts for all material in the detector, and the production of analogue signals, just like in the real detector.

4.2 Background simulation

For the simulation of the standard model background processes (see sec. 2.3) the aforementioned Monte-Carlo generators are used. Table 3 offers an overview of the samples for each of the relevant backgrounds.

For the QCD multijet background a set of H_T -binned samples were used, where H_T is defined as scalar sum of transverse momenta of all jets in the event. They were produced with MAD-GRAPH at leading order for the hard subprocess and Pythia8 for showering and hadronization (after *MLM* matching). The samples for the *W*+Jets and *Z*+Jets processes (with the bosons decaying hadronically) were produced with the same generator combination, while for the inclusive diboson samples (*WW*,*WZ*,*ZZ* with no specific decay channel) Pythia8 was used for the simulation of the hard subprocess as well. The $t\bar{t}$ sample was produced with POWHEG +Pythia8.

To normalize the simulation to the collected dataset, the events in all Monte-Carlo samples are scaled to the integrated luminosity $\mathcal{L}_{int} = 35.9 \text{ fb}^{-1}$ of the recorded Data:

$$w_{\text{Luminosity}} = \mathscr{L}_{int} \cdot \frac{\sigma}{N_{\text{Events}}}$$
 (4.3)

4.3 Signal Simulation

For the simulation of the signal process the framework of a standard model extending effective field theory (SMEFT - see section 2.2.1) is used. The framework is distributed in the form of a FEYNRULES [53] model [54–57] so it can be interpreted by generators. For the production of the signal sample MADGRAPH5_AMC@NLO was used together with the SMEFT model to simulate the hard subprocess of the vector boson scattering at leading order (see Feynman diagram in figure 2.3).

The SMEFT model introduces 18 dimension-8 Operators $\mathcal{O}_i^{(k)}$ that are added to the standard model Lagrangian. The generator uses additional Feynman diagrams with quartic gauge boson interactions, where the quartic gauge couplings are altered according to the model's parameters. The 18 operators can be scaled independently by their respective scaling parameter $F_i^{(k)}$. In the generation process, the internal reweighting feature [58] of MADGRAPH was used to scan over each parameter $F_i^{(k)}$ and reweight the process amplitude to produce event weights for the parameter range $[F_{i,\min}^{(k)}, \cdots, 0, \cdots, F_{i,\max}^{(k)}]$. Here the reweighting procedure uses

Sample	σ [pb]	N _{Events}	MC Generator
QCD $(H_T \in [300, 500] \text{ GeV}/c^2)$	347500	37514715	MadgraphMLM+PYTHIA8
QCD $(H_T \in [500, 700] \text{ GeV}/c^2)$	32060	62229758	MadgraphMLM+PYTHIA8
QCD $(H_T \in [700, 1000] \text{ GeV}/c^2)$	6829	45260499	MadgraphMLM+PYTHIA8
QCD $(H_T \in [1000, 1500] \text{ GeV}/c^2)$	1207	15125299	MadgraphMLM+PYTHIA8
QCD $(H_T \in [1500, 2000] \text{ GeV}/c^2)$	120	11773017	MadgraphMLM+PYTHIA8
QCD $(H_T \in [2000, \infty] \text{ GeV}/c^2)$	25.25	6035623	MadgraphMLM+PYTHIA8
W+jets with $W \rightarrow q\bar{q'}$	95.14	1026517	MadgraphMLM+PYTHIA8
Z+jets with $Z \rightarrow q\bar{q}$	41.34	994930	MadgraphMLM+PYTHIA8
WW	118.7	994017	PYTHIA8
WZ	47.13	990003	PYTHIA8
ZZ	16.52	993154	PYTHIA8
$t \bar{t}$	831.76	155159297	POWEHEG+PYTHIA8

Table 3: Overview of the background samples used in the analysis. Besides the name also the theoretical cross-section σ , the produced number of events N_{Events} and the used Monte-Carlo generator is listed

the matrix element $|\mathcal{M}_{h}^{GEN}|$ of the generated process and the matrix element $|\mathcal{M}_{h}^{SMEFT}|$ of the SMEFT process with a specific configuration of the parameters $F_{i}^{(k)}$ to calculate the new weight w_{SMEFT} with

$$w_{\text{SMEFT}} = \frac{|\mathcal{M}_h^{\text{SMEFT}}|^2}{|\mathcal{M}_h^{\text{GEN}}|^2} \cdot w_{\text{GEN}}.$$
(4.4)

The advantage of using weights is that events do not have to be generated for every single point in the parameter range. For the determination of systematic uncertainties additional weights are generated with the same procedure. One set of weights for PDF uncertainties and one set for QCD scale (μ_R , μ_F) uncertainties (see sec. 5.3 for details on the determination) are also calculated. For the PDF weights the PDF4LHC_NLO_MC_PDFAS [59,60] set was used, which offers a nominal PDF (at $\alpha_S = 0.118$), along with 100 variations representing the uncertainties. For the QCD scale weights, the nominal renormalization scale μ_R and factorization scale μ_F are set to the central transverse mass scale, which corresponds to the geometric mean of $\mu_i^2 = p_{T,i}^2 + m_i^2$ when two heavy particles are in the process [42]. Here these are the two bosons from the vector boson scattering. Both μ_R and μ_F are then getting varied by a factor two up and *down* together².

For the hadronization and parton shower simulation Pythia8 was used, while matching was not necessary as MADGRAPH was not configured to produce additional partons.

For the analysis six signal samples have been produced for the six possible final states of the vector bosons scattering with W^{\pm} or Z bosons. Table 4 offers an overview of these six samples with the number of produced events N_{Events} and the theoretical cross section σ calculated from MADGRAPH.

² they are varied in the permutations: $(\times 1, \times 1), (\times 1, \times 2), (\times 2, \times 2), (\times 1, \div 2), (\div 2, \div 2), (\times 2, \times 1), (\div 2, \times 1)$

Sample	σ [pb]	N _{Events}		
W^+W^+	8.1	43460		
W^+W^-	86.28	41943		
W^-W^-	1.19	43942		
W^+Z	8.70	45460		
$W^{-}Z$	3.34	41454		
ZZ	28.57	489931		

Table 4: Overview of the produced signal samples. In the first column the two bosons in the final state of the vector boson scattering are listed. The additional columns show the theoretical cross-section σ , the produced number of events N_{Events} .



Figure 4.3: Distributions of the reconstructed diboson mass, for both ZZ signal events, as well as the QCD multijet background. Several variations of two selected operators are shown in each plot.

In Figure 4.3 one can see two example distributions of the dijet mass of the two leading AK8 jets of the event. Besides the steeply falling blue QCD background, the plots also include the distributions from the *ZZ* process at different SMEFT parameter reweighting points of the operators \mathcal{O}_{M0} and \mathcal{O}_{T0} . The cross section for larger dijet invariant masses is increased by the anomalous couplings of the SMEFT model. This is a main feature of the analysis as discussed in section 5. The anomalous quartic gauge couplings also result in interference terms with the standard model. Having tested the size of the interference contribution however, it was shown to be a subdominant effect compared with the pure anomalous gauge coupling terms and was therefore neglected. Therefore, only aQGC Feynman diagrams were taken into account in the production of the signal samples.

4.4 Event Selection

To reduce the large amount of background and to improve the sensitivity to a signal, a variety of selection criteria on the events are introduced. The first selection is the choice of the L1 and HLT trigger. The analysis in this thesis uses a dataset with the same jet-based trigger combination as used in [30]. Here the requirements on events include selections on H_T . This trigger selection reaches an efficiency of 99% for events with an reconstructed invariant mass of the two jets with largest transverse momentum in the event $m_{jj} > 1050$ GeV, and at least one jet with a reconstructed mass of the jet $m_j > 65$ GeV.

The signal signature consists of four jets, where two of them originate from hadronic decays of boosted bosons, thus being reconstructed as larger-radius AK8 jets (our *VV* jets) and two of them are forward jets produced in association with the vector boson fusion, reconstructed as AK4 jets (also called *VBF* jets). Both jet collections in each event have to fulfill initial kinematic criteria:

VV	AK8 jets:	• $p_{T,AK8} > 200 \text{ GeV}$
		• $ \eta_{T,AK8} < 2.5$
VBF	AK4 jets:	• $p_{T,AK4} > 30 \text{ GeV}$
		• $ \eta_{T,AK4} < 5.0$

To isolate events with our signal signature, a set of selections is applied in two steps. First the *VV* selection, which focuses on the AK8 jets, is applied. The *VBF* selection introduces requirements on the AK4 jets. The *VV* selection consists of the following criteria for the leading two AK8 jets:

- At least two AK8 jets $N_{AK8} \ge 2$,
- an AK8 dijet mass $M_{\rm jj-AK8} > 1050$ GeV,
- a separation in the η -plane $|\Delta \eta_{ij-AK8}| < 1.3$,
- a soft-drop mass in the range of 65 GeV < $M_{\rm SD}$ < 105 GeV,
- a N-Subjettiness of $0 \le \tau_{21} 0.45$.

The two leading AK8 jets (those with largest transverse momentum p_T) are considered to be the diboson jets. The selections on the dijet mass M_{jj-AK8} and the separation of these jets in the η -plane $|\Delta \eta_{jj-AK8}|$ is applied first to achieve the aforementioned maximum trigger efficiency. After requiring at least two AK8 jets the selections on the substructure variables are introduced. These aim to better identify AK8 jets originating from W^{\pm} and Z bosons. Therefore the softdrop mass window is chosen around the masses of both bosons.



Figure 4.4: Distributions of the two leading AK8 jets where the initial kinematic criteria are applied and the events passed the selection criteria on the M_{jj-AK8} , $|\Delta\eta_{jj-AK8}|$, and all remaining up the ones on the variable of interest: (a) the transverse momentum p_T , (b) η , (c) invariant dijet mass M_{jj-AK8} , separation $|\Delta\eta|$, the softdrop mass M_{SD} and the N-Subjettiness τ_2/τ_1 . Each plot shows the recorded data with the corresponding statistical uncertainty, all used SM background as one stacked histogram and their cumulative statistical uncertainty, and the signal process ZZ with a given parameter $F_{T0} = 12.5$. The QCD Background is scaled by f_{OCD} (see Eq. 4.6).

The distribution of each of the variables used to select AK8 jets is shown in Figure 4.4, where each plot includes the selection criteria on the invariant dijet mass M_{jj-AK8} and the separation $|\Delta \eta_{jj-AK8}|$ (to reach the maximum trigger efficiency), as well as all aforementioned requirements up to that on the variable of interest.

Since the QCD simulation tends to over-predict the scale of the QCD contribution compared to data, a QCD scale f_{OCD} has been introduced into the plots to compensate for this:

$$N_{\text{Data}} = N_{\text{QCD}}^{\text{MC}} * f_{\text{QCD}} + \sum_{i} N_{i}^{\text{MC}}$$
(4.5)

$$\Rightarrow f_{\rm QCD} = \frac{N_{\rm Data} - \sum_i N_i^{\rm MC}}{N_{\rm QCD}^{\rm MC}}$$
(4.6)

Here N_i^{MC} is the event yield of the respective background process, and N_{Data} is the event yield in the data sample. The sum runs over all backgrounds, except QCD.

The plots show that the AK8 jets from the signal are quite central and have a larger transverse momentum p_T and invariant dijet mass M_{jj-AK8} than the background. Furthermore looking at the separation $|\Delta \eta_{jj-AK8}|$, the signal peaks towards zero, while the background tends to higher values. The substructure variables also show good separation. While a peak at the masses of the respective bosons $m_{W/Z}$ can be observed in the distribution of the softdrop jet mass for the signal, the background in this region remains relatively flat. The N-subjettiness peaks as expected for the signal AK8 jets with two subjets at low values, in contrast to the background which has less subjets.

To ensure that the AK4 jets do not overlap with the chosen AK8 jets, a requirement on their distance to the AK8 jets ΔR is placed. The distance $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ between each of the AK4 jets and each of the two AK8 jets is calculated. Every AK4 jet that is within $\Delta R < 1.2$ is removed from the collection of AK4 jets in the event. The *VBF* selection aims to isolate the two AK4 jets in the forward η region by requiring:

- At least two AK4 jets $N_{\text{AK4}} \ge 2$,
- a separation in the η -plane $|\Delta \eta_{jj-AK4}| > 3.0$,
- an invariant AK4 dijet mass $M_{\rm jj-AK4}$ > 1.0 TeV.

Figure 4.5 shows the distributions of the variables used in the VBF Selection, where each plot includes the VV Selection and the overlap removal between AK4 and AK8 jets. The distribution of the transverse momentum p_T of the AK4 jets produced in association with the vector boson fusion is falling slower than that of the background jets. In addition, it can already be seen in the η distribution that the VBF jets are located in the forward region. The selections on the invariant AK4 dijet mass M_{jj-AK4} and the separation $|\Delta \eta_{jj-AK4}|$ have been optimized to achieve the best sensitivity of the analysis.



Figure 4.5: Control plots that show the distribution including the requirements of the VV selection and the overlap removal between AK4 and AK8 jets for : (a) transverse momentum p_T of the two leading AK4 jets, η of the two leading AK4 jets, total number of AK4 jets, separation $|\Delta \eta_{jj-AK4}|$, and invariant dijet mass of the two leading AK4 jets. Each plot shows the recorded data with the corresponding statistical uncertainty, all used SM background as one stacked histogram and their cumulative statistical uncertainty, and the signal process ZZ with a given parameter $F_{T0} = 12.5$. The QCD Background is scaled by f_{OCD} .



Figure 5.1: Fit of AK8 dijet mass ($M_{jj,AK8}$) distribution in ZZ Channel with a SMEFT scaling parameter set to $F_{T0} = 12.5 \text{ TeV}^{-4}$. For the fit a bifurcated Gaussian with different widths σ_{left} and σ_{right} left and right from the maximum value and the mean μ .

5 Analysis

This analysis aims to test the sensitivity of the all-jets final state of vector boson scatterings $(VV \rightarrow V_f V_f, \text{ where } V_f = W^{\pm}, Z)$ in the search for anomalous quartic gauge couplings, by deriving exclusion limits on parameters in a standard model extending effective field theory framework.

A shape analysis of the AK8 dijet mass distribution is performed, that compares the recorded data with an analytical model of the signal and background. Thus parametrizations of the signal and background distributions are needed. For the AK8 dijet mass distribution a bifurcated Gaussian was chosen. As an example, one can see in Figure 5.1 a fit of said bifurcated Gaussian to the AK8 dijet mass distribution in the ZZ channel, where a SMEFT scaling parameter is set to an example value ($F_{T0} = 0.36 \text{ TeV}^{-4}$).

The shape analysis will perform a simultaneous fit of the signal and background functions to data in two categories. There is the *pass-VBF selection* category, which is composed of all events that pass both VV and VBF selections, as discussed in Section 4.4. The *fail-VBF selection* category however includes events that passed the *VV* selection but failed the VBF selection. The signal to background ratio (*S*/*B*) in the *fail-VBF* category is much smaller than in the *pass-VBF* category (see Figure 5.2). In addition, the *fail-VBF* category has much better statistics, so the respective fit is much better and the category is QCD dominant. Thus the event yield for the *pass-VBF* can be extracted from the *fail-VBF* category under the assumption that the background has the same shape in both categories. This will be tested in both



Figure 5.2: Result of fits in a signal injection test. The pseudo-data includes events from the QCD samples as well as the ZZ signal sample. On the right is the result of the fit in the *fail-VBF* category and on the right the result in the *pass-VBF* category.

Monte-Carlo simulations and in Sideband region data.

5.1 Background Estimation

For the estimation of the background shape, a parametrization by the following functional form is used:

$$f_b^{2\text{par}} = \frac{p_0}{(x/\sqrt{s})^{p_1}},\tag{5.1}$$

where $p_{0,1}$ are free parameters and x is the invariant dijet mass M_{jj-AK8} . The division by the center of mass energy \sqrt{s} is used only to keep the parameters of order (*O*)(1). The assumption that the background shape in both categories can be described by this form has been verified in a "closure" test with QCD multijet simulation. In this test, f_b was fitted to the simulated QCD events, in both *fail-VBF* and *pass-VBF* categories using a maximum likelihood method. The result can be seen in Figure 5.3. Both plots show the simulated QCD events in black markers. The fitted functions and the QCD MC events are normalized to a total integrated yield of 1. The left plot shows the QCD MC events in the *fail-VBF* category and the corresponding fitted function f_b^{2par} (red). On the right plot, one can see both the fit from the left plot, the *fail-VBF* region, (red) as well as the QCD MC events in the *pass-VBF* category, and their respective fit (blue).

To test the compatibility of the fit function from *fail-VBF* with QCD MC events from *pass-VBF* the corresponding χ^2 is calculated with

$$\chi^{2} = \sum_{i}^{N} \frac{(y_{i}^{\text{fit,fail-VBF}} - y_{i}^{\text{MC,pass-VBF}})^{2}}{(\sigma_{i}^{\text{MC,pass-VBF}})^{2}},$$
(5.2)



Figure 5.3: (a): Fit of simulated QCD events (Signal Region) in the *fail-VBF* (!VBF) category and (b): in red same function as in (a) and in blue the fit of simulated QCD events in the *pass-VBF* (VBF) category.

where *N* denotes the number of non-zero bins of the pass-VBF histogram in the range where the *fail-VBF* fit was performed. The values $y_i^{\text{MC,pass-VBF}}$ and $\sigma_i^{\text{MC,pass-VBF}}$ are the bin content and the bin error of the *i*-th bin of the histogram with QCD MC events in the *pass-VBF* category. Finally, there is $y_i^{\text{fit,fail-VBF}}$, which is the function value of the fit function evaluated at the center of the *i*-th bin.

With this definition one gets a $\chi^2/dof = 1.03$, with which compatibility can be observed. Whilst this method has therefore been verified in QCD MC simulation, one would also like to test it in data. In order to do this, a sideband region, with no overlap with the signal region, is defined. The definition of this region and the associated closure test are now discussed.

5.1.1 Validation in Data Sideband Region

In the signal region, it is important to include as much of the signal as possible, while keeping the contributions from standard model backgrounds as small as possible. For the definition of the sideband region one aims to do the opposite. While selecting an event topology that is as close as possible to the signal region, one aims to select a large number of background events, with as little signal contamination as possible.

For this analysis the signal region (SR) is defined as the full event selection discussed in Section 4.4. The sideband region (SBR) is defined almost identically to the signal region, except for a different selection criterion on the softdrop jet mass $M_{\rm SD}$. Similarly there are both *fail-VBF* and *pass-VBF* sideband regions. While for the signal region both leading AK8 jets are required to have a soft-drop mass in the window 65 GeV $< M_{\rm SD} < 105$ GeV, in the sideband region the leading AK8 jet is required to have a minimum soft-drop mass of $M_{\rm SD} \ge 135$ GeV, while the second leading AK8 jet stays in the window of the signal region (65 GeV $< M_{\rm SD} < 105$ GeV).



Figure 5.4: Soft-drop mass of the leading AK8 jet in: (a) the signal region and (b) the sideband region.

In Figure 5.4a one can see that in the signal region the signal peaks around the mass of the Z boson in the softdrop mass distribution of the leading jet, which separates it from the relatively flat background. On the other hand Figure 5.4b shows the same distribution in the sideband region. Here the ZZ signal is much smaller than the background. Figure 5.5 shows additional plots of various distributions with events that pass the sideband region selection. The plots demonstrate that the simulation reasonably models the topology of the AK4 jets. This supports the closure test performed in simulation and confirms that it can be trusted to validate the background estimation procedure.

The closure test with data in the sideband region can be performed. However the function with two parameters, $f_b^{2\text{par}}$, is not sufficient to describe the shape of the data in the sideband, that can be understood because the number of data events is significantly higher in the sideband region than in the signal region. Thus another free parameter p_2 is introduced:

$$f_b^{3\text{par}} = \frac{p_0 \cdot (1 - (x/\sqrt{s}))^{p_2}}{(x/\sqrt{s})^{p_1}}$$
(5.3)

and is fitted to the data as seen in Figure 5.6. On these plots one can see the sideband data distributions and the respective fits of the parameterization function $f_b^{3\text{par}}$. Both have been normalized to unity. Both *fail-VBF* and *pass-VBF* categories are shown, with the fit function in the former also shown in the latter to compare with data. Testing the compatibility of the fit function from *fail-VBF* with data from *pass-VBF*, one has a $\chi^2/\text{dof} = 0.85$. Thus, a good compatibility is observed, and our fundamental assumption that the shape from the *fail-VBF* region can be used in the *pass-VBF* region is verified.



Figure 5.5: Control plots that show the distribution with the events that passed the sideband region selections: (a) transverse momentum p_T of the two leading AK4 jets, (b) η of the two leading AK4 jets, (c) the total number of AK4 jets and (d) the invariant dijet mass of the two leading AK4 jets. Each plot shows the recorded data with the corresponding statistical uncertainty, all used SM background as one stacked histogram and their cumulative statistical uncertainty, and the signal process ZZ with a given parameter $F_{T0} = 12.5$. The QCD Background is scaled by f_{OCD} .



Figure 5.6: Invariant AK8 dijet mas distributions in sideband region: (a) data events and their fit in the *fail-VBF* (!VBF) category, and (b): data events and their fit (blue) in the *pass-VBF* (VBF) category. Also shown in (b) is the fit from the *fail-VBF* category (red).

5.2 Limit calculation method

In this section the procedure to compute exclusion limits on the scaling parameters of the standard model extending effective field theory is explained. The procedure utilizes a modified version of the CL_s frequentist method [61] as described in [62, 63]. As mentioned above we are analysing the shape of the AK8 dijet mass M_{jj-AK8} in two categories: the *fail-VBF* and the *pass-VBF* selection category. First a likelihood function \mathcal{L}_i for each category *i* is constructed with

$$\mathscr{L}_{i}(\text{data}|\boldsymbol{\mu},\boldsymbol{\theta}_{i}) = \text{Poisson}(\text{data}|\boldsymbol{\mu} \cdot \boldsymbol{s}(\boldsymbol{\theta}) + \boldsymbol{b}(\boldsymbol{\theta})) \cdot \boldsymbol{p}(\boldsymbol{\tilde{\theta}}_{i}|\boldsymbol{\theta}_{i}).$$
(5.4)

Here $p(\tilde{\theta}_i | \theta_i)$ are probability density functions for the *i*-th category, that describe nuisance parameters θ_i in order to take systematic uncertainties into account. The nominal values of these uncertainties is denoted by $\tilde{\theta}_i$. The nuisance parameter may be shared between categories. The *data* can be represented by the actual recorded data, or pseudo-data, used for example for a *signal injection* test. The event yield of signal and background processes are denoted by $s(\theta)$ and $b(\theta)$, respectively. The signal yield has an additional factor μ , the signal strength modifier, that allows one to scale the signal contribution from its expected value ($\mu = 1$) to no contribution ($\mu = 0$). *Poisson* refers to the unbinned likelihood over *k* data events

$$k^{-1}[(\mu \cdot S \cdot f_s(M_{\rm jj-AK8}) + B \cdot f_b(M_{\rm jj-AK8})) \cdot e^{-(\mu \cdot S + B)}],$$
(5.5)

where *S* and *B* are the total expected signal and background event rates, respectively, and f_s and f_b are the respective probability density functions of the AK8 dijet mass M_{jj-AK8} . f_s is extracted from Monte-Carlo simulations with all parameters fixed, while f_b is constrained in the signal+background fit to data and not pre-determined from simulation.

To take both categories into account a combined likelihood function $\mathscr{L}(\mu, \theta)$ is defined as the product

$$\mathscr{L}(\boldsymbol{\mu}, \boldsymbol{\theta}) = \prod_{i} \mathscr{L}_{i}(\boldsymbol{\mu}, \boldsymbol{\theta}_{i}), \qquad (5.6)$$

where *i* runs over the two categories *fail-VBF* and *pass-VBF*. For the comparison of the compatibility of the *data* and the signal+background (with signal strength modifier μ) and *background only* hypothesis (with $\mu = 0$) a test statistic q_{μ} is calculated:

$$q_{\mu} = -2 \ln \frac{\mathscr{L}(\mu, \hat{\boldsymbol{\theta}}_{\mu})}{\mathscr{L}(\hat{\mu}, \hat{\boldsymbol{\theta}})}, \qquad \hat{\mu} \le \mu.$$
(5.7)

Here $\hat{\theta}_{\mu}$ maximises the likelihood (for a given signal strength modifier μ), thus it is called maximum likelihood estimator for the *signal+background* hypothesis. The parameters $\hat{\theta}$ and $\hat{\mu}$ provide together the global maximum of the likelihood. To keep the upward fluctuations of the signal ($\hat{\mu} > \mu$) out of consideration the requirement $\hat{\mu} \le \mu$ is introduced. Additionally for the calculation of the *observed* limits the requirement $\hat{\mu} > 0$ is introduced as there are no negative signal rates expected for the considered signal.

For observed limits, first the observed value of q_{μ}^{obs} for the given signal strength modifier μ has to be found. After finding the maximum likelihood estimators $\hat{\theta}_{0}^{obs}$ and $\hat{\theta}_{\mu}^{obs}$ for the respective hypotheses, the *pdfs* $f(q_{\mu}|\mu, \hat{\theta}_{\mu}^{obs})$ and $f(q_{\mu}|0, \hat{\theta}_{0}^{obs})$ are constructed using toy Monte-Carlo pseudo-datasets. The nuisance parameters are fixed for the generation of the toys, while they are allowed to float in the fits for the evaluation of q_{μ} . With the pdfs one can derive the *p*-values corresponding to the respective hypothesis as follows:

$$p_{\mu} = P(q_{\mu} \ge q_{\mu}^{\text{obs}} | \text{signal+background}) \qquad = \int_{q_{\mu}^{\text{obs}}}^{\infty} f(q_{\mu}) | \mu, \hat{\theta}_{\mu}^{\text{obs}}) dq_{\mu} \tag{5.8}$$

$$1 - p_b = P(q_\mu \ge q_\mu^{\text{obs}} | \text{background only}) \qquad \qquad = \int_{q_0^{\text{obs}}}^{\infty} f(q_\mu) | 0, \hat{\boldsymbol{\theta}}_{\boldsymbol{0}}^{\text{obs}}) dq_\mu. \tag{5.9}$$

The confidence level for a given signal strength modifier μ is then given by

$$CL_s(\mu) = \frac{p_{\mu}}{1 - p_b}.$$
(5.10)

The *signal+background* hypothesis can be excluded when the confidence level is less than a value α for $\mu = 1$: CL_s $\leq \alpha$. To gain the upper limit on μ at the common 95% confidence level, μ is varied until CL_s = 0.05 is reached. In this analysis, the asymptotic variant of this method is used to set the observed and expected limits. The expected limit is defined as the limit under the assumption of the background-only model, i.e. $\mu = 0$. This quantifies the sensitivity of the analysis. Here it will be derived together with its uncertainy band using a Asimov dataset, which incorporates the background estimation and the nominal nuisance parameter. The

confidence level CL_s can be calculated directly with

$$CL_s = \frac{1 - \Phi(\sqrt{q_{\mu}})}{\Phi(\sqrt{q_{\mu,A}} - \sqrt{q_{\mu}})},$$
(5.11)

where Φ is the cumulative distribution of a standard Gaussian and $q_{\mu,A}$ is the test statistic derived from the Asimov dataset [62]. The upper median expected limit and the associated uncertainty band is given by

$$\mu_{\text{up}+N} = \sigma \cdot (\Phi^{-1}(1 - \alpha \Phi(N)) + N).$$
(5.12)

Here Φ^{-1} is the quantile function of the standard Gaussian while σ follows $\sigma^2 = \frac{\mu^2}{q_{\mu,A}}$. The 95% CL_s median expected limit follows with $\alpha = 0.05$ and N = 0:

$$\mu_{up}^{med} = \sigma \cdot \Phi^{-1} (1 - 0.5 \cdot \alpha) = \frac{(\mu_{up}^{med})^2}{q_{u,A}} \cdot \Phi^{-1} (0.975)$$
(5.13)

$$\mu_{up}^{med} = \frac{q_{\mu,A}}{\Phi^{-1}(0.975)},\tag{5.14}$$

where $\mu = \mu_{up}^{med}$ was assumed for the calculation of σ .

To calculate limits on the scaling parameters of the standard model extending effective field theory operators (aQGC parameters) the signal samples include event weights for ranges of these parameters as mentioned in Section 4.3. Using these the distribution of the AK8 dijet mass distribution can be weighted for individual parameter values and filled in a histogram. The aforementioned signal parametrization can be fitted to each of the reweighted distributions and, together with the background fit, serve as inputs for the limit setting procedure. In the end, this scan over the aQGC parameters produces limits on the signal strength modifier μ as a function of the aQGC parameter value F_i . Both expected limits with uncertainty bands, along with the observed limits, will be produced. The respective limit on the aQGC parameter can be finally extracted from the point where the signal strength modifier reaches $\mu = 1$. To test if the procedure is sensitive to the aQGC signal process a signal injection test has been performed. For this test pseudo-data is used, which consist of QCD background and ZZ signal events. The result in figure 5.2 shows the fit of the signal + background shape to the pseudo-data in the *fail-VBF* category on the left side and on the right in the *pass-VBF* category.

5.3 Systematic Uncertainties

In the calculation of the limits on the aQGC parameters, systematic uncertainties are taken into account via the nuisance parameters in the likelihood function as described above. These can vary the normalization and/or the shape of the AK8 dijet mass distribution. For the background all parameters in the fit are left floating and no additional uncertainties are



Figure 5.7: Distribution of the invariant AK8 dijet mass for different jet energy scales. In the middle the nominal jet energy scale is used, while left and right respectively an up and down variation by one standard deviation was used. All distributions were fitted with a bifurcated Gaussian, with the same width parameters in all 3 distributions.

considered, since it is believed that these are already included by the statistical uncertainties of the fit, which was confirmed in simulation and data sidebands. All the following uncertainties are considered for the signal.

5.3.1 Luminosity

As the Monte-Carlo samples are weighted to the integrated luminosity \mathcal{L}_{int} of the used data sample, the uncertainty on the luminosity measurement has to be taken into account as an uncertainty on the signal event yield. The uncertainty is estimated to be 2.5% [20].

5.3.2 Pileup

The uncertainty resulting from the measurement of the minimum bias cross section, which is decisive in the estimation of pileup, is estimated to be 2% on the normalisation [30].

5.3.3 V-Tagging

The efficiency with which we identify vector bosons differs between data and Monte-Carlo. This introduces a uncertainty that is taken into account as an uncertainty on the final signal event yield, and was estimated with the procedure described in [64]. For the used working point used in this analysis (65 GeV < $M_{\rm SD}$ < 105 GeV; $0 \le \tau_{21} \le 0.45$), this amounts to 6%. As we tag two bosons in this analysis a total uncertainty of 12% is included.

5.3.4 Jet Energy Scale

The uncertainty on the jet energy scale is estimated by the CMS Collaboration [29]. For this analysis the invariant AK8 dijet mass distribution was fitted with a bifurcated Gaussian for the nominal value of the jet energy scale, as well as for the "up" and "down" variations by one standard deviation. For the latter two, the widths of the bifurcated Gaussian were fixed to



Figure 5.8: Distribution of invariant AK8 dijet mass for: (a) the nominal parton density function of NNPDF3.0 (black) and PDF4LHC (green). Additionally the standard deviation of 100 variations with respect to the PDF4LHC nominal pdf are included as a red band. (b) the nominal factorization scale μ_F and renormalization scale μ_R (in black) and an envelope constructed with variation combinations of both scales.

the value from the "nominal fit". Allowing all 3 parameters to vary is too many degrees of freedom for the observed shift in the distribution, and leads to overly-large uncertainties and poorly-estimated fit parameters. The fitted distributions are shown in Figure 5.7. It can be seen that the variation of the jet energy scale shifts the mean μ of the Gaussian by roughly 1% and the event yield by roughly 6%. While the shift of the event yield is included as an uncertainty on the signal normalisation, the shift of the mean is taken into account as a shape uncertainty.

5.3.5 Parton Density Function

For the calculation of the uncertainty on the parton density functions, the signal samples contain, as mentioned in Section 4.3, additional weights for 100 variations of the nominal pdf. For each weight, a histogram of the invariant AK8 dijet mass was filled. For each bin of the histogram, the standard deviation with respect to the nominal pdf x_{nom} is calculated with

$$\sigma = \sqrt{\frac{\sum_{i}^{N} (x_{i} - x_{\text{nom}})^{2}}{N - 1}},$$
(5.15)

where N = 100 are the variations on the nominal pdf. The distribution of the relative standard deviation was then fitted with a constant function. Figure 5.8a show the result of this procedure, where the green distribution corresponds to the nominal pdf of the pdf set PDF4LHC_NLO_MC_PDFAS [59]. This pdf set is recommended for BSM search and is an envelope of the three pdf sets: MMHT14,CT14 and NNPDF3.0. The MC variant was chosen over the hessian because the pdf set with which the sample was generated (NNPDF3.0 [36]) only includes these. While the red band is the calculated standard deviation the black distribution and the its statistical uncertainty originates from the NNPDF3.0 pdf set. Resulting from the fit a uncertainty on the signal normalisation of 5.5% is included. Although the relative standard deviation is not constant with respect to the invariant dijet mass, in the region with data ($M_{jj-AK8} \lesssim 2.5$ TeV), with higher statistics it is more constant and better represented with our choice of 5.5%.

5.3.6 μ_R, μ_F - Scales

The strong coupling constant α_s is not a static constant but varies ("runs") as a function of the energy scale at which it is evaluated, in order to absorb the scale associated with regularising high energy divergences. This choice of scale μ_R at which to evaluate $\alpha_s(\mu_R)$ is not concrete, but varies between generators. For example, in madgraph it is set to the central transverse mass scale, which corresponds to the geometric $\mu_i^2 = p_{T,i}^2 + m_i^2$ as mentioned in 4.3. One can therefore vary this scale, in order to determine the uncertainty associated with the scale choice. The scale is varied up and down by a factor of 2. In this analysis, because the hard process has no strong couplings, varying the renormalization scale has no impact upon the final result.

Writing the total cross section in the form of Equation 4.2, the hard scattering process is factorised out from the process-independent parton distribution functions. This relies on the PDFs absorbing the collinear low energy divergences. Similar to the regularisation of high energy divergences, the PDFs now depend on a scale, the factorisation scale μ_F . Again, there is not one "correct" choice of scale, and we estimate an uncertainty by varying the scale μ_F up and down by a factor of 2. The effect of this variation is clearly visible in Figure 5.8b

The envelope of the six variation histograms is taken as uncertainty. The distribution of that uncertainty is fitted with a constant function which results in an uncertainty of 21% in the worst case.

For the uncertainty of both the parton density and the renormalization- and factorization scales the linear dependence on the invariant AK8 dijet mass is neglected.

6 Results

Figure 6.1 presents the final distribution of the invariant AK8 dijet mass after the total VV+VBF selection is applied. The standard model background consists mostly of the QCD multijet events. As described in Section 4.4, the QCD histogram has been scaled to improve the agreement between data and simulation. Its distribution, in contrast with that of the signal, is sharply falling. There are no predicted background events with a AK8 dijet mass larger than 2.6 TeV. The aQGC signal on the other hand peaks at approximately 3 TeV, with a long tail to higher masses, separating it clearly from the standard model background. The plot also includes the analysed data. There are no excesses visible in the data, and shows generally good agreement with the Monte-Carlo background simulation. This already shows that no new physics or other deviations from the standard model have been observed in this analysis, and thus one expects that the observed and expected limits will be similar.



Figure 6.1: Distribution of the invariant AK8 dijet mass after applying the full VBF selection as discussed in Section 4.4. Data is shown in black markers. The SM backgrounds from MC simulation are shown as filled histograms, with the checked region showing their statistical uncertainty. The signal for ZZjj is shown in the black line.

In the following, the results of the limit setting procedure (described in Section 5.2) are presented and discussed.

The procedure is performed in the program COMBINE [61–63], which reports the expected and observed asymptotic frequentist CL_s limits. An example limit plot for the parameter F_{T6}



Figure 6.2: Invariant AK8 dijet mas distributions in signal region: (a) data events and their fit in the *fail-VBF* (!VBF) category, and (b): data events and the fit from the *fail-VBF* category. Also listed in (b) is the χ^2 /ndf and probability of the comparison between the fit in the *fail-VBF* category and the data in in the *pass-VBF* category.

is shown in Figure 6.3. Here the median expected limit is the dashed black line, while the observed is the continuous black line. The green and yellow areas correspond to the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty band of the expected limit, respectively. Since each aQGC scales the signal symmetrically, the exclusion limits are also symmetric about 0.

Figure 6.2 shows the signal data distributions and the fit of the parameterization function $f_b^{2\text{par}}$, both normalized to unity. Both *fail-VBF* and *pass-VBF* categories are shown, with the fit function of the *fail-VBF* category. Testing the compatibility of the fit function from *fail-VBF* with data from *pass-VBF*, one has a $\chi^2/\text{dof} = 0.61$. Thus, a good compatibility is observed, and our fundamental assumption that the shape from the *fail-VBF* region can be used in the *pass-VBF* region is verified.

The limits on the aQGC parameter itself are obtained by finding the intersection of the exclusion limit and the signal strength modifier $\mu = 1$. In the plot these intersections are drawn for the median expected limit as a filled black arrow with a continuous black tail, for the lower and upper uncertainty on each median expected limit as hollow black arrows with dashed black tails and for the observed limits as hollow grey arrows with dashed grey tails.

One of those plots has been produced for each combination of aQGC parameter and vector boson scattering channel. With 18 parameters and eight analysed channels there are calculated 144 pairs of expected and observed limits. Although technically only six signal samples have been produced, in this analysis also the combinated channels VV (sum of all six samples) and ssWW (sum of W^+W^+ and W^-W^- samples) are taken into account. Tables 5 and 6 summarise the resulting expected and observed limits, respectively. Here the empty cells are corresponding to combinations of a channel and aQGC parameter that has no sensitivity at all, due to missing contributions of the operator to the specific vertex (see table 2). The



Figure 6.3: Upper limits on the aQGC parameter $F_{\rm T6}$ derived in the ZZ channel. The dashed black line is the median expected limit at the 95% confidence level. The continuous black line is the observed limit derived from the 2016 dataset. The green and yellow bands are the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands on the expected limit, respectively.

values in the square brackets on the other hand refer to the parameter range that was used in the reweighting process during the signal sample generation. Here this sampling over the parameter range was not sufficiently narrow enough to set exclusion limits at that specific channel - parameter combination. This means that with a Monte-Carlo sample that uses a smaller reweighting range (or finer sampling) an exclusion limit will be found, that is definitely smaller than the bounds of the current range.

Compared to the existing literature limits quoted in Section 1, the observed limits on several aQGC parameters are partially improved by this analysis. If one compares the literature limits obtained in comparable channels, with the respective limits from this analysis, one can see that many of the observed limits set more stringent constraints on aQGC parameters than the existing limits.

More specifically, comparing the ssWW channel, a better limit on four $(F_{M1}, F_{M7}, F_{T1}, F_{T2})$ of the seven parameters was obtained in this analysis than set by the existing CMS ssWW analysis. In the ZZ channel, this analysis sets more stringent limits on all three of the parameters (F_{T0}, F_{T8}, F_{T9}) currently constrained by the existing ZZ analysis.

Considering the total sum over all VV channels, for eight parameters (F_{M1} , F_{M7} , F_{T0} , F_{T1} , F_{T2} , F_{T6} , F_{T8} , F_{T9}) this analysis sets the most stringent limits, whilst for another eight (F_{M0} , F_{M2} , F_{M3} , F_{M4} , F_{M5} , F_{M6} , F_{T5} , F_{T7}), although a limit was not explicitly set, it was shown to be within a range that improves upon the current literature limits.

	median expected asmyptotic 95% CL_s exclusion limits [TeV ⁻¹]							
aQGC parameter	literature limit		VV	ssWW	ZZ	W^+W^-		
F _{S0}	(-7.7,7.7)	ssWW	$-18^{+3.1}_{-4.3}, 20^{+2.8}_{-3}$	$-19^{+3.9}_{-4.8}, 19^{+3.9}_{-4.8}$	$-53^{+7.6}_{-11}$, $53^{+7.6}_{-11}$	-58^{+11}_{-14} , 58^{+11}_{-14}		
F _{S1}	(-21.8,21.8)	ssWW	[-30,30]	$-67^{+12}_{-18}, 67^{+12}_{-18}$	$-48_{-7.3}^{+6.6}, 48_{-7.3}^{+6.6}$	[-30, 30]		
F _{M0}	(-4.2,4.2)	$\gamma\gamma \rightarrow WW$	[-3,3]	$-7.8^{+1.4}_{-1.7}, 7.8^{+1.4}_{-1.7}$	[-3,3]	[-3,3]		
F _{M1}	(-8.7,9.1)	ssWW	$-4.2^{+0.68}_{-0.75}, 4.2^{+0.68}_{-0.75}$	$-9.4^{+1.4}_{-2.3}, 9.4^{+1.4}_{-2.3}$	$-9.4_{-1.2}^{+0.7}, 9.4_{-1.2}^{+0.7}$	$-4.7^{+0.69}_{-0.75}, 4.7^{+0.69}_{-0.75}$		
F _{M2}	(-26,26)	Wγ	[-5,5]		[-5,5]	[-5,5]		
F _{M3}	(-43,44)	Wγ	[-8,8]		$-12^{+1.4}_{-1.6}$, $12^{+1.4}_{-1.6}$	[-8,8]		
$F_{\rm M4}$	(-40,40	Wγ	[-8,8]		[-8,8]	[-8,8]		
F_{M5}	(-65,65)	Wγ	[-13,13]		$-25^{+1.9}_{-3.3}, 25^{+1.9}_{-3.3}$	[-13, 13]		
$F_{\rm M6}$	(-11.9,11.8)	ssWW	[-6,6]	$-16^{+2.8}_{-3.5}, 16^{+2.8}_{-3.5}$	[-6,6]	[-6,6]		
F _{M7}	(-13.3,12.9)	ssWW	$-7^{+0.8}_{-0.89}, 7^{+0.8}_{-0.89}$	$-14^{+2.4}_{-3.3}, 14^{+2.4}_{-3.3}$	$-18^{+1.7}_{-1.9}, 18^{+1.7}_{-1.9}$	$-7.8^{+0.77}_{-1.8}$, $7.8^{+0.77}_{-1.8}$		
F _{T0}	(-0.46,0.44)	ZZ	$-0.21^{+0.015}_{-0.017}, 0.21^{+0.015}_{-0.017}$	$-0.66^{+0.16}_{-0.12}, 0.66^{+0.16}_{-0.12}$	$-0.47^{+0.025}_{-0.054}$, $0.47^{+0.025}_{-0.054}$	$-0.21^{+0.015}_{-0.017}, 0.21^{+0.01}_{-0.01}$		
$F_{\rm T1}$	(-0.28,0.31)	ssWW	$-0.19^{+0.022}_{-0.034}, 0.19^{+0.022}_{-0.034}$	$-0.25^{+0.039}_{-0.057}, 0.25^{+0.039}_{-0.057}$	$-0.58^{+0.023}_{-0.11}$, $0.58^{+0.023}_{-0.11}$	$-0.32^{+0.058}_{-0.076}$, $0.32^{+0.05}_{-0.07}$		
$F_{\rm T2}$	(-0.89,1.02)	ssWW	$-0.47^{+0.053}_{-0.058}, 0.47^{+0.053}_{-0.058}$	$-0.75^{+0.11}_{-0.17}, 0.75^{+0.11}_{-0.17}$	$-1.2^{+0.079}_{-0.15}$, $1.2^{+0.079}_{-0.15}$	$-0.53^{+0.052}_{-0.12}$, $0.53^{+0.05}_{-0.12}$		
$F_{\rm T5}$	(-3.8,3.8)	Wγ	[-0.7, 0.7]		$-1.2^{+0.088}_{-0.097}$, $1.2^{+0.088}_{-0.097}$	[-0.7, 0.7]		
$F_{\rm T6}$	(-2.8,3.0)	Wγ	$-0.98^{+0.097}_{-0.21}$, $0.98^{+0.097}_{-0.21}$		$-1.5^{+0.17}_{-0.27}, 1.5^{+0.17}_{-0.27}$	$-2^{+0.34}_{-0.52}, 2^{+0.25}_{-0.51}$		
$F_{\rm T7}$	(-7.3,7.7)	Wγ	$-1.7^{+1.7}_{-0.41}, 1.7^{+1.7}_{-0.41}$		$-3.8^{+0.36}_{-0.4}$, $3.8^{+0.36}_{-0.4}$	$-2^{+0.42}_{-0.47}$, $2^{+0.42}_{-0.47}$		
F _{T8}	(-0.84,0.84)	ZZ	$-0.8^{+0.087}_{-0.12}, 0.8^{+0.087}_{-0.12}$		$-0.8^{+0.087}_{-0.12}$, $0.8^{+0.087}_{-0.12}$			
F _{T9}	(-1.8,1.8)	ZZ	$-1.7^{+0.18}_{-0.25}$, $1.7^{+0.18}_{-0.25}$		$-1.7^{+0.18}_{-0.25}$, $1.7^{+0.18}_{-0.25}$			

median expected asmyptotic 95% CL_e exclusion limits [TeV⁻¹]

	median expected asmyptotic 95% CL_s exclusion limits [TeV ⁻¹]							
aQGC parameter	literatur	e limit	W^+W^+	$W^{-}W^{-}$	W^+Z	W^-Z		
F _{S0}	(-7.7,7.7)	ssWW	$-21_{-5.7}^{+4.6}, 21_{-5.7}^{+4.6}$	$-43^{+8.9}_{-12}$, $43^{+8.9}_{-12}$	$-57^{+9.5}_{-14}$, $57^{+9.5}_{-14}$	$-74_{-20}^{+14}, 75_{-19}^{+15}$		
F _{S1}	(-21.8,21.8)	ssWW	$-71^{+14}_{-19}, 71^{+14}_{-19}$	$-1.6e + 02^{+28}_{-46}$, $1.6e + 02^{+28}_{-49}$	$-86^{+14}_{-21}, 86^{+14}_{-21}$	$-1.5e + 02^{+27}_{-38}$, $1.5e + 02^{+27}_{-37}$		
F _{M0}	(-4.2,4.2)	$\gamma\gamma \rightarrow WW$	$-8.1^{+1.4}_{-1.9}, 8.1^{+1.4}_{-1.9}$	$-20^{+3.8}_{-5.4}, 20^{+3.8}_{-5.4}$	$-8.1^{+1.7}_{-1.9}, 8.1^{+1.7}_{-1.9}$	$-13^{+2.3}_{-3.4}, 13^{+2.3}_{-3.4}$		
F _{M1}	(-8.7,9.1)	ssWW	$-9.8^{+1.6}_{-2.4}, 9.8^{+1.6}_{-2.4}$	$-24_{-6.3}^{+4.5}, 24_{-6.3}^{+4.5}$	$-11^{+2.1}_{-2.9}, 11^{+2.1}_{-2.9}$	$-19^{+3.8}_{-4.7}, 19^{+4.1}_{-4.5}$		
F _{M2}	(-26,26)	Wγ			$-12^{+2.4}_{-2.9}$, $12^{+2.4}_{-2.9}$	$-23_{-6.3}^{+4.5}, 23_{-6.3}^{+4.5}$		
F_{M3}	(-43,44)	Wγ			$-18^{+3.3}_{-4.5}$, $18^{+3.3}_{-4.5}$	$-29^{+6.2}_{-8.6}, 29^{+6.2}_{-8.6}$		
F_{M4}	(-40,40	Wγ			[-8,8]	[-8,8]		
F _{M5}	(-65,65)	Wγ			[-13, 13]	$-18^{+3.8}_{-4.2}, 18^{+3.8}_{-4.2}$		
F _{M6}	(-11.9,11.8)	ssWW	$-16^{+2.9}_{-3.9}, 16^{+2.9}_{-3.9}$	$-41_{-11}^{+7.5}, 41_{-11}^{+7.5}$	$-20^{+4.6}_{-5}$, $16^{+1.9}_{-2.7}$	$-26^{+4.6}_{-6.7}, 26^{+4.6}_{-6.7}$		
F_{M7}	(-13.3,12.9)	ssWW	$-14^{+2.6}_{-3.6}, 14^{+3.8}_{-3.6}$	$-35_{-9.2}^{+6.6}, 35_{-9.2}^{+6.6}$	$-14^{+2.4}_{-3.2}, 19^{+3.3}_{-3.6}$	$-25^{+3.9}_{-6.5}$, $25^{+3.9}_{-6.5}$		
F _{T0}	(-0.46,0.44)	ZZ	$-0.67^{+0.16}_{-0.13}, 0.71^{+0.12}_{-0.16}$	$-1.7^{+0.17}_{-0.46}$, $1.7^{+0.17}_{-0.45}$	$-0.73^{+0.098}_{-0.16}$, $0.73^{+0.098}_{-0.16}$	$-1.2^{+0.17}_{-0.3}$, $1.2^{+0.17}_{-0.3}$		
F _{T1}	(-0.28,0.31)	ssWW	$-0.25^{+0.046}_{-0.053}$, $0.25^{+0.039}_{-0.058}$	$-0.68^{+0.11}_{-0.17}$, $0.68^{+0.11}_{-0.17}$	$-0.37^{+0.055}_{-0.089}, 0.37^{+0.055}_{-0.089}$	$-0.56^{+0.091}_{-0.15}$, $0.56^{+0.091}_{-0.15}$		
F _{T2}	(-0.89,1.02)	ssWW	$-0.76^{+0.12}_{-0.17}, 0.76^{+0.12}_{-0.17}$	$-2.1_{-0.48}^{+0.35}, 2.1_{-0.48}^{+0.35}$	$-1.1^{+0.11}_{-0.28}$, $1.1^{+0.16}_{-0.27}$	$-1.7^{+0.28}_{-0.46}$, $1.7^{+0.28}_{-0.46}$		
$F_{\rm T5}$	(-3.8,3.8)	Wγ			$-1.7^{+0.29}_{-0.33}, 1.7^{+0.29}_{-0.33}$	$-2.7^{+0.46}_{-0.62}, 2.7^{+0.46}_{-0.62}$		
F _{T6}	(-2.8,3.0)	Wγ			$-1.5^{+0.22}_{-0.36}$, $1.5^{+0.22}_{-0.36}$	$-2^{+0.36}_{-0.51}, 2^{+0.36}_{-0.51}$		
$F_{\rm T7}$	(-7.3,7.7)	Wγ			$-4.1^{+0.88}_{-0.98}, 3.9^{+0.39}_{-0.65}$	$-5.3^{+0.91}_{-1.4}$, $5.3^{+0.91}_{-1.4}$		
F _{T8}	(-0.84,0.84)	ZZ						
F _{T9}	(-1.8, 1.8)	ZZ						

Table 5: All expected limits obtained with the procedure explained in Section 5.2. Shown are the limits for each of the six channels, along with the sum of the same sign WW (ssWW) samples, and the sum of all samples (VV).

	median observed asmyptotic 95% CL_s exclusion limits [TeV ⁻¹]									
aQGC parameter	literatur	e limit	VV	ssWW	W^+W^+	W ⁻ W ⁻	W^+W^-	W^+Z	$W^{-}Z$	ZZ
F _{S0}	(-7.7,7.7)	ssWW	-16, 18	-17, 17	-19, 19	-36, 36	-51, 51	-52, 52	-70, 71	-49, 49
F _{S1}	(-21.8,21.8)	ssWW	[-30,30]	-59, 59	-63, 63	-1.4e + 02, 1.4e + 02	[-30,30]	-78, 78	-1.4e + 02, 1.4e + 02	-45, 45
F _{M0}	(-4.2,4.2)	$\gamma\gamma \rightarrow WW$	[-3,3]	-6.8, 6.8	-7,7	-18, 18	[-3,3]	-7, 7	-11, 11	[-3,3]
F _{M1}	(-8.7,9.1)	ssWW	-3.7, 3.7	-8.3, 8.3	-8.5, 8.5	-21, 21	-4.2, 4.2	-9.7, 9.7	-17, 17	-8.8, 8.8
F _{M2}	(-26,26)	Wγ	[-5,5]				[-5,5]	-10, 10	-21, 21	[-5,5]
F _{M3}	(-43,44)	Wγ	[-8,8]				[-8,8]	-1.8e + 02, -1.8e + 02	-26, 26	-11, 11
F _{M4}	(-40,40	Wγ	[-8,8]				[-8,8]	[-8,8]	[-8,8]	[-8,8]
F _{M5}	(-65,65)	Wγ	[-13,13]				[-13,13]	[-13,13]	-16, 16	-23, 23
F _{M6}	(-11.9,11.8)	ssWW	[-6,6]	-14, 14	-14, 14	-36, 36	[-6,6]	-17, 15	-23, 23	[-6,6]
F _{M7}	(-13.3,12.9)	ssWW	-6.4, 6.4	-12, 12	-12, 12	-31, 31	-7.2, 7.2	-13, 17	-22, 22	-17, 17
F _{T0}	(-0.46,0.44)	ZZ	-0.2, 0.2	-0.58, 0.58	-0.6, 0.6	-1.6, 1.6	-0.2, 0.2	-0.65, 0.65	-1, 1	-0.46, 0.46
F _{T1}	(-0.28,0.31)	ssWW	-0.18, 0.18	-0.21, 0.21	-0.22, 0.22	-0.6, 0.6	-0.27, 0.27	-0.32, 0.32	-0.49, 0.49	-0.56, 0.56
F _{T2}	(-0.89,1.02)	ssWW	-0.43, 0.43	-0.66, 0.66	-0.67, 0.67	-1.8, 1.8	-0.49, 0.49	-0.99, 0.95	-1.5, 1.5	-1.1, 1.1
F _{T5}	(-3.8,3.8)	Wγ	[-0.7,0.7]				[-0.7,0.7]	-1.5, 1.5	-2.3, 2.3	-1.1, 1.1
F _{T6}	(-2.8,3.0)	Wγ	-0.91, 0.91				-1.7, 1.8	-13, -13	-1.7, 1.7	-1.4, 1.4
F_{T7}	(-7.3,7.7)	Wγ	-1.5, 1.5				-1.6, 1.6	-3.4, 3.6	-4.7, 4.7	-3.5, 3.5
F _{T8}	(-0.84,0.84)	ZZ	-0.73, 0.73							-0.73, 0.73
F _{T9}	(-1.8,1.8)	ZZ	-1.6, 1.6							-1.6, 1.6

Table 6: All observed limits obtained with the procedure explained in Section 5.2. Shown are the limits for each of the six channels, along with the sum of the same sign WW (ssWW) samples, and the sum of all samples (VV).

7 Conclusion and Outlook

In this thesis a search for anomalous quartic gauge couplings in vector boson scatterings was presented. Anomalies in the quartic gauge couplings would indicate deviations in the mechanism of electroweak symmetry breaking and a sign for physics beyond the Standard Model of particle physics. This is the first search of its type that analyses vector boson scattering processes in which both W^{\pm} or Z bosons decay fully hadronically, thus producing an all-jets final state.

The analysed *pp*-collision data was recorded at the Large Hadron Collider with the CMS detector at a center of mass energy of $\sqrt{13}$ TeV and corresponds to a total integrated luminosity of $\mathcal{L}_{int} = 35.9 \text{ fb}^{-1}$.

Deviations caused by anomalous quartic gauge couplings would occur in the scattering cross sections of the di-boson processes at high energies, which is why this analysis looks for signatures with high momentum bosons. Therefore an event selection that utilizes the signal signature with two Lorentz-boosted vector bosons is introduced. Due to their large transverse momentum p_T , the bosons each form highly collimated particles as they decay hadronically. These will be reconstructed as single "fat" jets with substructure. Variables describing this substructure are used to tag the bosons, enriching the aQGC signal processes, while the standard model background can be rejected to a large degree. The estimation of the prominent QCD multijet background by a two-parameter function was extensively tested and finally applied in a shape analysis procedure. Here the assumption was made that the shape is the same in the orthogonal categories *fail-VBF* and *pass-VBF*. Events that fail the VBF selection (*fail-VBF* category) outlast a first selection part, which focuses on the fat jets, but are rejected in the second part, where jets are selected that are produced in association with the bosons. The assumption that a fit to the *fail-VBF* category can describe the *pass-VBF* category was confirmed in QCD simulation in the signal region, and in data in a sideband region.

A simultaneous maximum likelihood fit to the invariant AK8 dijet mass distribution in the *fail-VBF* and *pass-VBF* categories is performed to test for presence of signal in the data distributions and derive expected and observed upper 95% C.L. exclusion limits on the aQGC parameters. There is a good agreement between data and the background-only hypothesis over the entire mass range and no visible excesses of data over the standard model. This shows that no new physics or other deviations from the standard model were found and that the observed and expected limits are very similar.

The presented analysis is sensitive to all combinations of W^{\pm} and Z pairs. When considering them all as signal in the analysis can provide the best limits for 16 out of 18 aQGC parameters. Searches from literature include analyses carried out in the channels ssWW and ZZ. Here this

analysis can set more stringent limits than those of existing analyses for four out of seven and two out of three compared aQGC parameters, respectively.

The presented result demonstrates the importance of this channel that has been explored for the first time, superseding current literature constraints. It can be further developed as follows.

When new signal samples with narrower parameter scans are produced, the limits, that are for now only referring to an upper limit due to the granularity of the current samples, could be further improved.

While in effective field theories the operators are treated with independent parameters, in real theories multiple operators would be correlated. In this analysis, all other aQGC parameters were set to zero for the scan over a single aQGC parameter. Thus correlations of the aQGC parameters among each other are not considered. With these simple 1D scans only a very limited statement can be made about the extent to which a real theory would be constraint. If 2D scans were performed instead, these correlations could be included in the calculation of two-dimensional limits.

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Erklärung

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Ort, Datum

Unterschrift

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