

Sensitivity of dimension-8 EFT operators to resonance signals in vector boson scattering

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Summary

Abstract

English:

Experimental evidence has shown that the Standard Model (SM) is not complete theory. Research for Beyond the Standard Model (BSM) particles are conducted at the Large Hadron Collider (LHC). With Run 2 Vector Boson Scattering (VBS) processes gained importance in the analysis of Triple Gauge Coupling (TGC) and Quadratic Gauge Coupling (QGC). In these process new physics are theorized and several theories suggest particles with a mass lower than 1 TeV. An Effective Field Theory (EFT) is introduced to describe a variety of different theories. In EFT an effective Lagrangian is derived containing operators for high mass dimensions. In this thesis dim-8 EFT operators are investigated in the scattering of a $W^\pm$ and a Z boson. The dim-8 operators are fitted against resonances in the range from 225 GeV to 1000 GeV. For studying the sensitivity the invariant mass and transverse mass are analyzed. The objective is to find the lowest resonances mass that can be described using dim-8 EFT operators and setting the EFT limits for these resonances.

Abstract

Deutsch:

Experimente haben gezeigt das, dass Standardmodell keine vollständige Theory ist. Am Large Hadron Collider wird nach Teilchen gesucht, die das Standardmodell erweitern. Mit Run 2 wurden Vektorbosonen Streuungen (VBS) wichtiger da sich einfach dreifach und vierfach Kopplungen untersuchen lassen. Diese Prozesse werden als gute Kandidaten für neue Physik gesehen und moderne Theorien schlagen neue Teilchen mit Masse kleiner als 1 TeV vor. Es können Effektive Feld Theorien (EFT) eingeführt werden, die eine große Anzahl dieser Theorien beschreiben können. In EFT wird eine effektive Lagrange Funktion definiert die Operatoren mit hohen Masse Dimensionen beinhalten. In dieser Arbeit werden dim-8 EFT Operatoren in der Streuung von $W^\pm$ und Z Bosonen untersucht. Die dim-8 Operatoren werden an Resonanzen gefittet mit Massen zwischen 225 GeV und 1000 GeV. Die Sensitivität wird für die invariante Masse und die transversale Masse analysiert. Mit dem Ziel die niedrigste Masse, die mit dim-8 EFT Operatoren beschrieben werden kann im $W^\pm Z$ festzulegen und EFT Limits für diese Resonanzen zu bestimmen.

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Acronyms

BSM Beyond the Standard Model. iii, 9, 14, 15, 18, 22, 31, 37, 39, 41

EFT Effective Field Theory. iii, 3, 9, 11, 12, 13, 14, 16, 17, 18, 21, 24, 25, 26, 27, 31, 37, 38, 39

GM Georgi-Machacek Model. 25, 26, 31, 38

LHC Large Hadron Collider. iii, 3, 5, 6, 18, 37

MSSM Minimal Supersymmetric Standard Model. 16

QGC Quadratic Gauge Coupling. iii, 13, 18, 25

SM Standard Model. iii, 3, 9, 11, 12, 13, 14, 15, 21, 22, 25, 26, 37, 38, 39

SMEFT Standard Model effective field theory. v, 12

SUSY Supersymmetry. 15, 16

TGC Triple Gauge Coupling. iii, 13, 18

UV Ultraviolet. 9, 11, 12, 14, 15, 16, 31, 37

VBS Vector Boson Scattering. iii, 13, 17, 18, 19, 31, 37

1 Introduction

The goal of all physics around the world is to understand nature. From the universe itself and huge objects like black holes described by Einstein's general theory of relativity down to the smallest objects the fundamental particles describe by the standard model (SM) of particle physics. The vast difference is not only size but also in time. The cosmological timescale is often millions of years while particle physics work with life times as low as 10–25s. All cases come with their own unique challenges and obstacles, but in a sense all are equal all are described by physics. Combining the different theory is however not trivial. The general relativity describes gravity but the quantum field theory and subsequently the SM doesn't include a particle that describes gravity. The search for a theory beyond the SM is an important aspect of modern physics. At the Large Hadron Collider (LHC) measurement for most aspect of particle physics are conducted. One of the aspects is the scattering of $W^\pm$ and the Z Boson and there interaction with the Higgs-Boson. This thesis focuses on the search for beyond the standard model particles in the $W^\pm Z$ scattering process using the Effective Field Theory (EFT) approach. EFT is often used for resonances with high energy compared to the invariant mass of the researched process. This thesis looks at low energy resonances with the main result being the lowest resonance energy possible that can be described by EFT. Chapter 2 focuses on the Large Hadron Collider (LHC) and the ATLAS experiment. While chapter 3 gives an introduction in to effective field theory, beyond the standard model physics and the $W^\pm Z$ vector boson scattering process. The event selection and the statistics used to analyze the data are discussed in chapter 4. In chapter 5 the results of the analysis are presented. The results discussed the EFT coefficients for different resonance masses and different cross-sections. Lastly chapter 6 summarizes the results and gives an outlook for further research.

2 Experimental Setup

2.1 Large Hadron Collider

CERN may be the most famous scientific institution in the world. One reason for this fame is the Large Hadron Collider (LHC)[1] build in 2008. The LHC is the largest circular collider in the world, famous for the first discovery of the Higgs-Boson. The two-ring-superconducting-hadron accelerator and collider are build in a 26.7 km tunnel beneath the border of France and Switzerland. This technological marble is only possible thanks to thousands of engineers, computer scientists and physicists around the world. Four large detectors ALICE, ATLAS, CMS and LHC and other smaller experiments are connected to the LHC. The LHC aims for a collision energy of 14 TeV and as of now Run-II achieved 13 TeV by accelerating particle beams up to 6.5 TeV.

The number of events per second N is given by:

$$\frac{dN}{dt} = L\sigma \quad (2.1)$$

σ is the cross-section of particles and L the luminosity defined as: ¹

$$L = \frac{N_b^2 n_b f \gamma}{5\pi \epsilon_n \beta^*} F \quad \text{with} \quad F = \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*} \right)^2 \right)^{-\frac{1}{2}} \quad (2.2)$$

N_b number of particles per bunch

n_b number of bunches

ϵ_n normalized transverse beam emittance

β^* beta function at collision point

F luminosity correction in the interaction point based on the crossing angle

With the start of Run-3 on April 22, 2022 a collision energy of 13.6 TeV is expected.

¹Equations taken from [1]

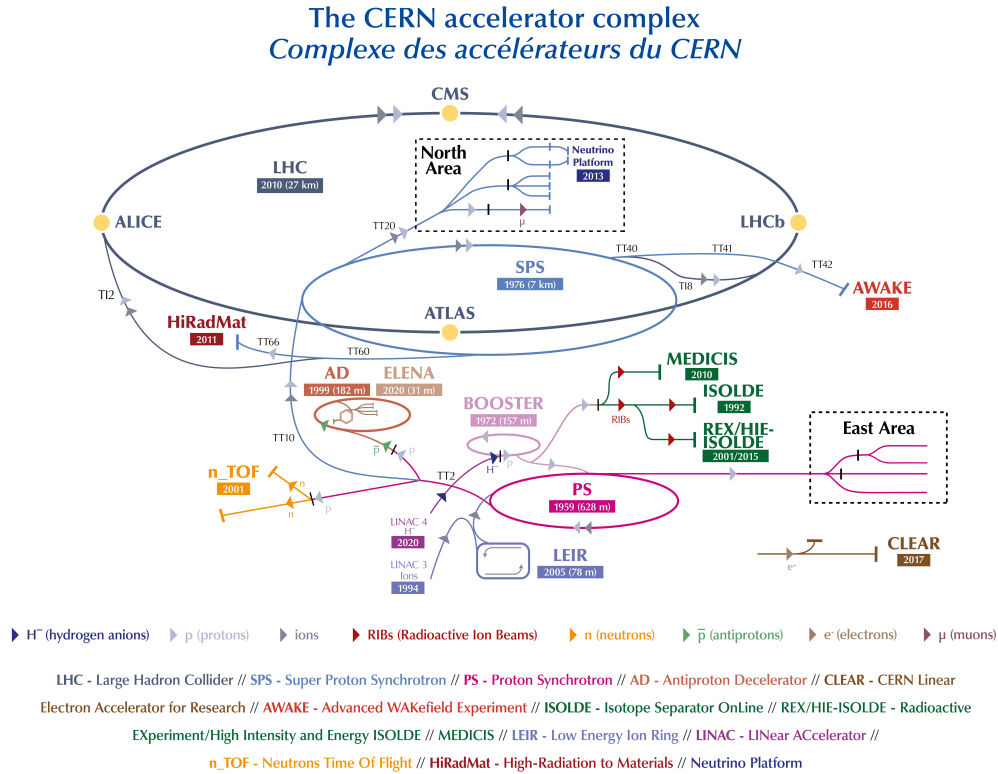


Figure 2.1: Schematic view of the LHC with all experiments [2]

2.2 ATLAS detector

ATLAS² the largest general-purpose detector is a part of the LHC experiments with more than 5500 scientists working on ATLAS experiments worldwide. The main goal is precision measurements but also Higgs search, extra dimension, dark matter and a wide variety of physics research is conducted. A short overview of the ATLAS detectors structure is shown here in figure 2.2a, but a detailed version can be read here [1].

Magnet System

The magnet system creates the magnetic field that bends the trajectory of the incoming particles in order to measure the momentum of said particles. For this purpose two superconducting toroide magnets create a magnetic field $B = 2$ T. The momentum can be calculated from the curvature r due to the Lorenz force.

$$r = \frac{p}{qB} \quad (2.3)$$

where $p = \gamma mv$ is the relativistic momentum and q the charge of the particle. High momentum-particles result in small curvature while low-momentum particles show a greater curvature.

²A Toroidal LHC ApparatuS

Inner Detector

The inner detector consists of three subdetectors. The ATLAS-Pixel detector is the innermost part surrounded by the semiconductor tracker(SCT) providing additional data for the curvature calculation. The outermost layer is the transition radiation tracker (TRT). Transition radiation is used to differentiate between fermions and hadrons.

Calorimeters The electromagnetic calorimeter and the Hadron calorimeter make up the calorimeter system. Particles that interact via electromagnetic force are measured in the electromagnetic calorimeter. Electrons or photons create particle showers in the electromagnetic calorimeter and no showers in the hadronic calorimeter while hadrons show traces in both and showers mostly in the hadronic calorimeter(as shown in 2.2b). This happens because hadrons have a higher mass and the cross-section is inverse proportional to the mass of the particle.

Myon Spectrometer Two different myon detectors are used for ATLAS experiments. First the precision chambers for spatial resolution measurements while the second detector is mainly used as a trigger. Interesting myon events can be analysed independent of other events as myon have heavy mass and don't decay though strong interactions, therefore only traces are visible in the first two detectors.

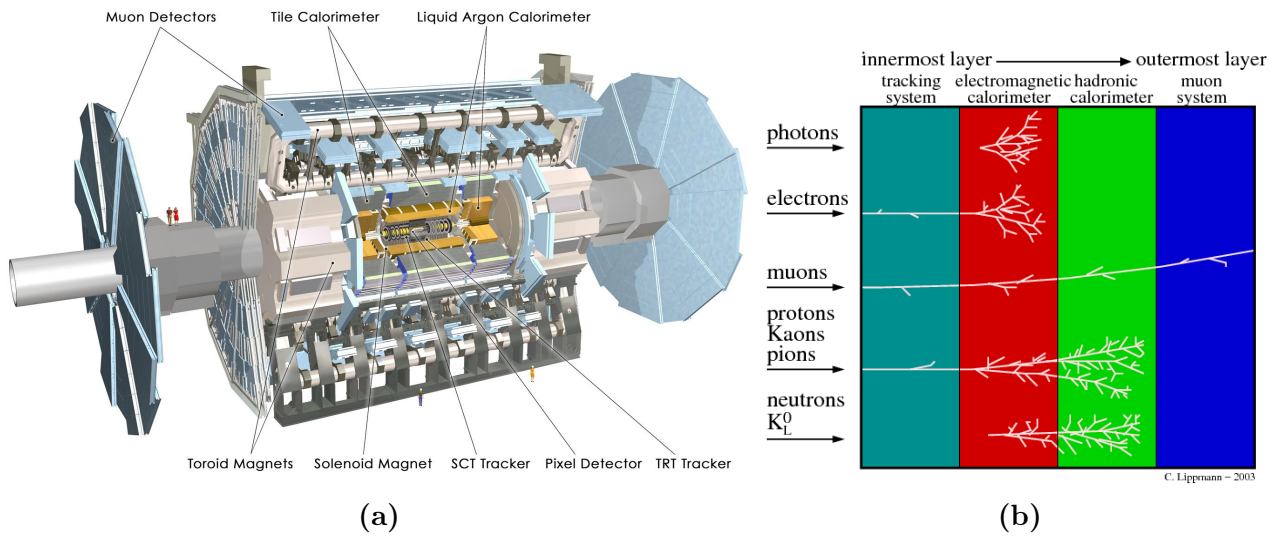


Figure 2.2: a) 3D of the ATLAS detectors with major components [3] b) Schematic of particle showers and traces inside the ATLAS detector [4]

3 Theoretical Foundation

3.1 Effective Field Theory

With the Standard Model (SM) physicist try to describe the elementary particles and interactions. It is successful in describing most processes in physics. But the SM is still incomplete. It can't describe phenomenons like gravity, neutrino masses, matter-antimatter asymmetry etc. This is where effective field theory (EFT) comes in. Here one looks at the SM as a low energy approximation of an underlying ultraviolet(UV) theory (figure 3.1). An in depth introduction into EFT is shown in [5] and [6].

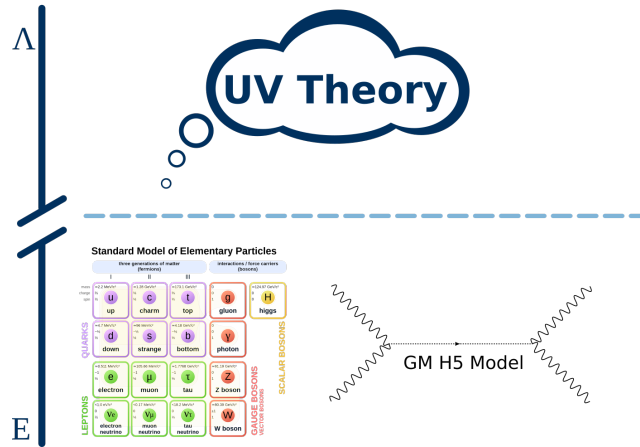
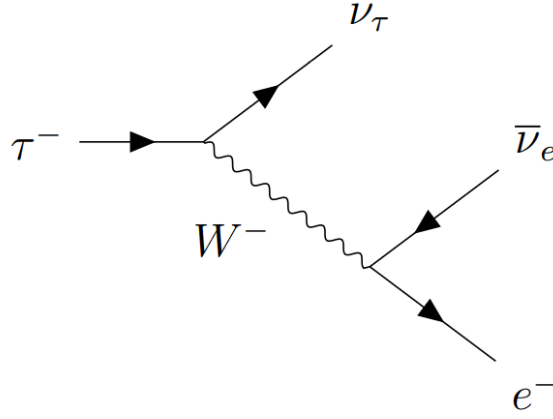


Figure 3.1: Sketch of the Basic EFT concept with the low energy observer having energy E and cutoff at Λ . The SM and BSM theory(here GM H5 Model [7]) are combined in the EFT. [8]

3.1.1 Fermi Theory on the example Tau Decay

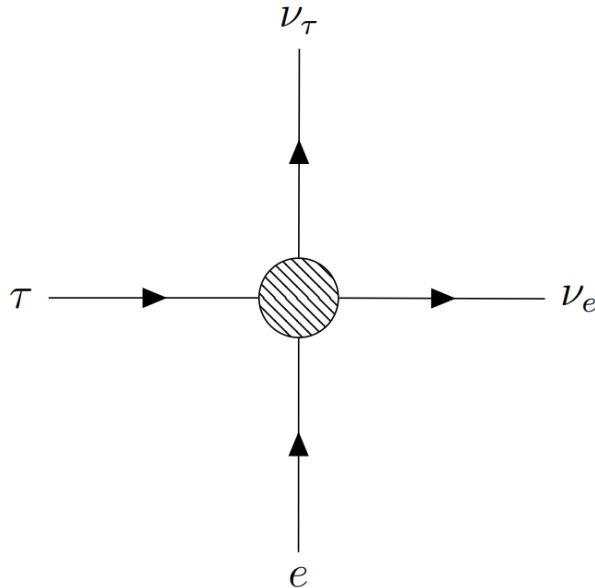
In 1933 Enrico Fermi proposed the Fermi theory in order to describe the β -decay. His theory was able to describe the weak coupling quite well without the former knowledge about the $W^\pm$ -Boson which was only later theorized in 1968 by Steven Weinberg, Sheldon Glashow and Abdus Salam. The $W^\pm$ -Boson was finally discovered in 1983. 50 years after Fermi's first successful description of an interaction involving the $W^\pm$ -Boson. Today one would call the Fermi theory the low-energy EFT of the $W^\pm$ -Boson. Let's try now to create a different Fermi theory but instead of describing the β decay[9], this theory will look at the τ -decay specifically

the decay mode $\tau \rightarrow \nu_\tau e^- \bar{\nu}_e$. Even though this is technically cheating since Fermi didn't have modern knowledge about the tensor structure of the weak interaction in Quantum Field Theory or the knowledge about Feynman diagrams. One can start by drawing the Feynman diagram and writing down the Lorenz invariant matrix element.



$$-i\mathcal{M}_{fi} = \left[\frac{g_W}{\sqrt{2}} \bar{u}(k_{\nu_\tau}) \frac{1}{2} \gamma^\mu (1 - \gamma^5) u(k_\tau) \right] \frac{g_{\mu\sigma} - \frac{k_\mu k_\sigma}{m_W^2}}{k^2 - m_W^2} \left[\frac{g_W}{\sqrt{2}} \bar{u}(k_e) \frac{1}{2} \gamma^\sigma (1 - \gamma^5) v(k_{\bar{\nu}_\tau}) \right] \quad (3.1)$$

In most low energy decay processes the momentum of the intermediate W^- -Boson is small compared to its mass. Therefore, one can approximate the propagator (3.2) in orders of the momentum k . But the matrix element in here written in orders of mass since these are more interesting for this thesis. In the Feynman diagram this can be expressed by collapsing the propagator into a single vertex.



$$\frac{-ig_{\mu\sigma} - \frac{k_\nu k_\sigma}{m_W^2}}{k^2 - m_W^2} \xrightarrow{|q|^2 \ll m_W^2} \frac{ig_{\mu\sigma}}{m_W^2} \left(1 + \frac{k^2}{m_w^2} + \frac{k^4}{m_W^6} + \mathcal{O}(k^6) \right) \quad (3.2)$$

$$\Rightarrow i\mathcal{M}_{fi} = \frac{g_W^2}{8m_W^2} [\bar{u}(k_{\nu_\tau})\gamma^\mu(1 - \gamma^5)u(k_\tau)] g_{\mu\sigma} [\bar{u}(k_e)\gamma^\sigma(1 - \gamma^5)v(k_{\bar{\nu}_e})] + \mathcal{O}(m_W^4) \quad (3.3)$$

One can now compare the result with the result Fermi would have gotten if he knew about the parity violation discovered by Wu in 1957.

$$i\mathcal{M}_{fi} = \frac{G_F}{\sqrt{2}} [\bar{u}(k_{\nu_\tau})\gamma^\mu(1 - \gamma^5)u(k_\tau)] g_{\mu\sigma} [\bar{u}(k_e)\gamma^\sigma(1 - \gamma^5)v(k_{\bar{\nu}_e})] \quad (3.4)$$

With $G_F \approx 4.5437957 \times 10^{14} J^{-2}$ being the Fermi constant which is typically measured in the muon decay. The $1/\sqrt{2}$ is added in order to not change the numerical value of G_F while considering the parity violation. From equation 3.3 and 3.4 one gets the following result.

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2} \quad (3.5)$$

Defining the expansion scale $\Lambda = m_W$ and the Wilson coefficient $c = \frac{g_W^2}{8}$ one can see that the matrix element has dimension 2. With this one can also write down a new effective Lagrangian without the $W^\pm$ -Boson. But the EFT described has to contain the tau, electron, their respective neutrino fields as well as the interaction Lagrangian.

$$\mathcal{L}_{EFT} = \frac{c}{\Lambda^2} (\bar{\nu}_\tau \bar{\gamma}_\rho \tau) (\bar{e} \gamma_\rho \nu_e) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right) \quad (3.6)$$

This Fermi theory is only valid for low energies since the scattering amplitude from the SM and the EFT would start to diverge once the energy gets close to the mass of the $W^\pm$ -Boson. The m_W defines the validity scale of the EFT in this case the Fermi theory. For energies higher than m_W the Fermi theory is no longer valid. One can increase the validity scale by including terms of higher dimension in Λ . In this example the Matrix element was derived from the SM and then compared the result with the result from Fermi in order to determine $\frac{c}{\Lambda}$. This requires knowledge about the UV theory which is not accessible in low-Energy measurements. As a result one has to make assumptions about the UV theory in order to construct the right EFT. This is called EFT Matching. The concept is shown in figure 3.2.

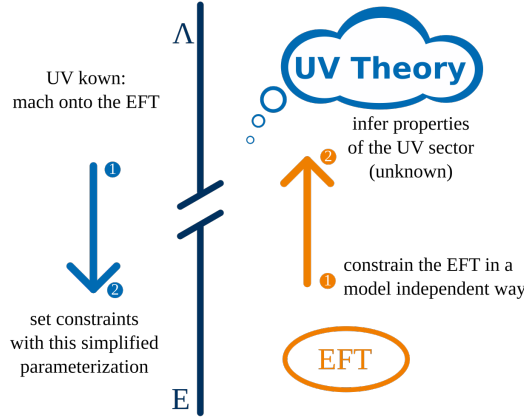


Figure 3.2: Schematic representation for the matching of an EFT to the UV theory using top-down and bottom-up matching method. [10]

3.1.2 Standard Model Effective Field Theory (SMEFT)

As the Name suggests The Standard Model effective field theory (SMEFT)[5] aims to extend the SM. Except the g-Factor of the myon the SM has been robust without meaningful deviations from experimental measurements. For this reason using a theory that keeps the $SU(3) \times SU(2) \times U(1)$ symmetry with the Higgs field breaking gauge symmetry is desirable. One can construct the Lagrangian from the gauge invariance of SM fields and allow arbitrarily large mass dimensions. With that any SMEFT Lagrangian can be written as:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \frac{1}{\Lambda^3} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \dots \text{ with } \mathcal{L}_i = \sum_i c_i^D \mathcal{O}_i^D \quad (3.7)$$

The operators $\mathcal{O}_i$ are constructed from the gauge invariance of the SM fields while the Wilson coefficients c_i contain the information on heavy degrees of freedom. Normally the heavy degrees of freedom are integrated out to have a renormalizable theory but are needed to describe high energy particles. The Wilson coefficients are constructed from the operator product expansion in 3.7 as shown in the Fermi theory(3.1.1). For a characteristic heavy scale Λ the operators are ordered by there dimension d_i fixing the dimension of their respective coefficients.

$$[\mathcal{O}_i] = d_i \longrightarrow c_i \sim \frac{1}{\Lambda^{d_i-4}} \quad (3.8)$$

The leading order $D = 4$ (marginal operator) term in 3.7 is the SM Lagrangian while deviations of the SM are described by operators with a dimension $D > 4$ also called irrelevant operators since they are suppressed by the scale E/Λ . Even though they are called irrelevant they often contain important information for processes with high energy. In a Fermi theory these contain information about processes with leading order flavour-change. Rele-

relevant operators $D < 4$ become relevant for energies close to the validity scale and only EFT's with relevant and marginal operators are normalizable making the predictions valid up to E/Λ .

Using knowledge about SM fields and known symmetries one can construct an operator basis. All allowed invariant structures are found using the SM fields and their symmetries at a dimension D . Removing all terms from the S-matrix that would result in the same physics provides the basis. The General choice of basis in the search for new physics is the Warsaw basis [10], other basis can be chosen as physics should be basis independent. In vector boson scattering (VBS) processes the Eboli basis[11] is commonly used because the operators can be categorized in longitudinal operators only containing covariant derivatives D^μ and a Higgs doublet fields Φ , transverse operators only containing field strength tensors $\widehat{W}_{\mu\nu}$ and mixed operators containing combinations. Most of the operators can be discarded since they don't contribute to $W^\pm Z$ processes leaving only six dimension-8 operators.

$$\begin{aligned}
\text{Longitudinal: } \quad \mathcal{O}_{S,1} &= [(D_\mu \Phi)^\dagger D_\mu \Phi] \times [(D^\nu \Phi)^\dagger D^\nu \Phi] \\
\text{Mixed: } \quad \mathcal{O}_{M,0} &= Tr[\widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu}] \times [(D_\beta \Phi)^\dagger D^\beta \Phi] \\
&\quad \mathcal{O}_{M,1} = Tr[\widehat{W}_{\mu\nu} \widehat{W}^{\mu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi] \\
\text{Transverse: } \quad \mathcal{O}_{T,0} &= Tr[\widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu}] \times Tr[\widehat{W}_{\alpha\beta} \widehat{W}^{\alpha\beta}] \\
&\quad \mathcal{O}_{T,1} = Tr[\widehat{W}_{\alpha\nu} \widehat{W}^{\mu\beta}] \times Tr[\widehat{W}_{\mu\beta} \widehat{W}^{\alpha\nu}] \\
&\quad \mathcal{O}_{T,2} = Tr[\widehat{W}_{\alpha\mu} \widehat{W}^{\mu\beta}] \times Tr[\widehat{W}_{\beta\nu} \widehat{W}^{\nu\alpha}]
\end{aligned}$$

3.1.3 EFT validity and unitarity violation

The time evolution of states in quantum mechanics is mathematically described by unitary operators. Time evolution without unitary operators is proposed in new approaches to quantum mechanics like Carl M. Bender's talk in 2020 at the TU-Dresden proposing a quantum theory including non Hermitian Hamiltonian [12]. Unitarity was a decisive concept for the inclusion of the Higgs field in the SM as it restored unitarity at tree level. EFT isn't a complete theory by extending the SM, the triple gauge coupling (TGC) and quadratic gauge coupling (QGC) processes are modified leading to unitarity violation. The expected behaviors of a unitary EFT is $\text{dim-6 interference} > \text{dim-6 quadratic} \sim \text{dim-8 interference} > \text{dim-8 quadratic}$. This however is not the case as dim-8 operators cause the scattering amplitude to grow asymptotically $\sim \Lambda^2$. This eventually leads to unitarity violation 3.3.

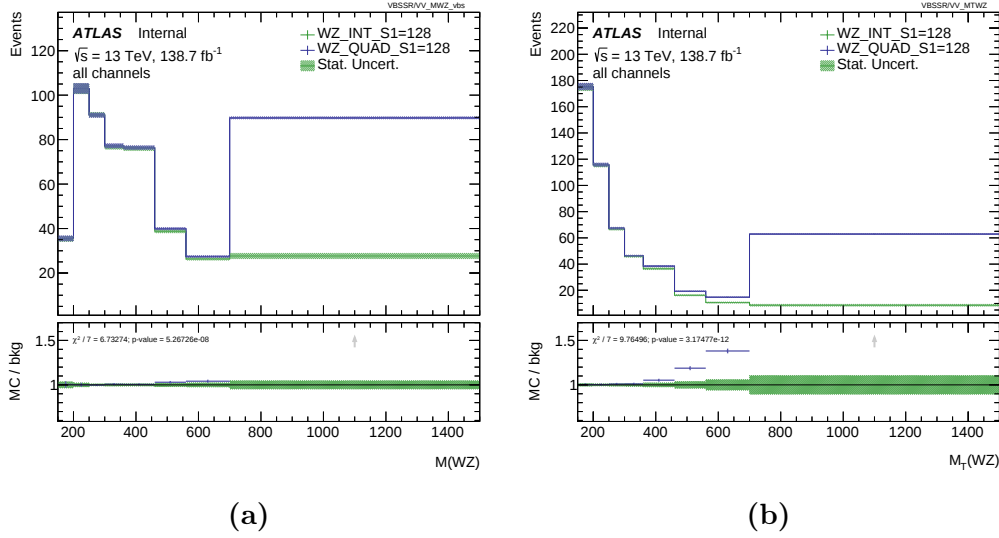


Figure 3.3: Comparison of interference term and quadratic term for the S1 parameters created with value S1=128. The quadratic term is bigger for higher energies since no unitarisation is used. **a)** $M(WZ)$, **b)** $M_T(WZ)$

One can now apply a cutoff at the validity scale $M = \Lambda$ but in practice the value of Λ is unknown and can only be gained by analysing data. This means that EFT predictions are only valid for an operator dependent unitarity limit. It should be noted that unitarity can be restored by using unitarisation. In ATLAS research the relatively simple K-matrix method is common tool for unitarisation as shown in [13]. This however does not restore EFT validity and makes connecting EFT results to UV theories harder. In conclusion the search for beyond the standard model (BSM) effects using EFT is only possible in an energy range as light states are not detectable and high Energy states are removed by the unitarity limit 3.4.

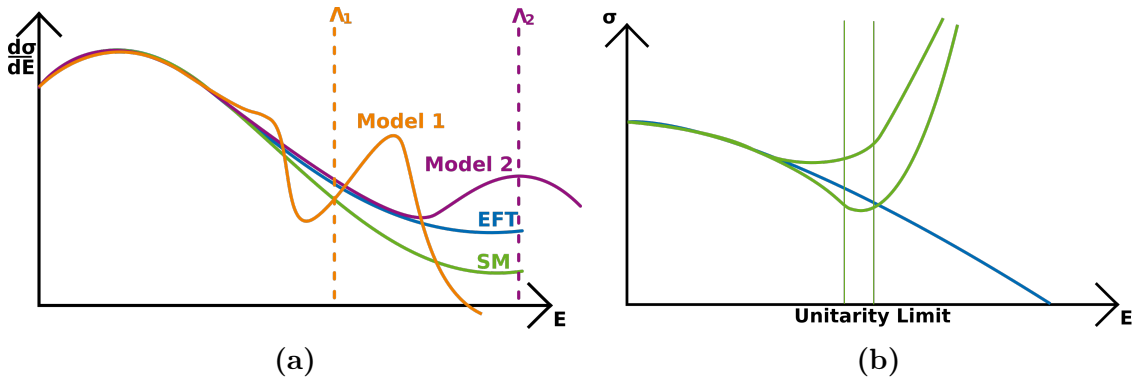


Figure 3.4: **a)** Not all models can be fitted using EFT only ones with energy scale higher than the SM [8] **b)** Schematic of unitarity limits the energy range changes depending on the cutoff [14]

3.2 BSM Theories

In 2012 the last particle predicted by the SM was detected at CERN, the Higgs Boson, yet again proving the success of the SM. But this also means no more free parameters in the SM for new particles. All interactions found obey the local $SU(3) \times SU(2) \times U(1)$ gauge symmetries [15] and more recent data only strengthens the SM prediction. While no data was found suggesting inconsistencies with the electroweak symmetry breaking $SU(2) \times U(1) \rightarrow U(1)$ and no new exotic particles are found between 0-2 TeV (appendix figure 8.1). This means physicist have to search for new interactions considering different interaction ranges and strengths (Figure 3.5).

- (a) Considerably weaker than gravity with infinite range
- (b) Shorter range than the weak interaction of any strength
- (c) Range between weak interaction and nuclear force and considerably weaker than the weak interaction

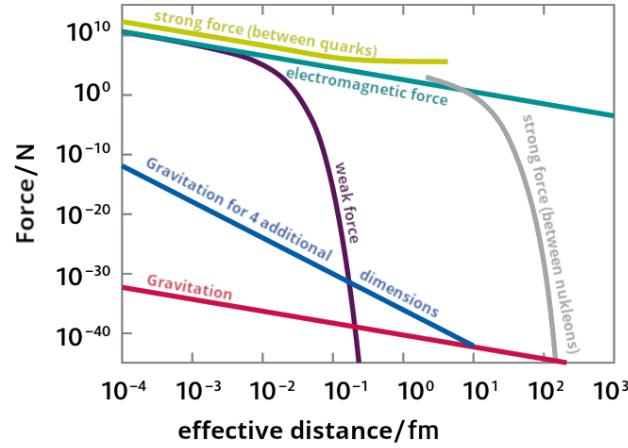


Figure 3.5: Interaction strength for different ranges of the Fundamental interactions. Although the Nuclear force isn't a fundamental it is shown in order to visualize point (c). [16]

There are various methods for finding BSM particles and as many theoretical models for new interactions, but these can generally be broken down in three categories.

The model specific search where one takes a well-defined model often describing a complete UV theory and tries to find the predicted particles in measurements. The most popular example for this is the Supersymmetry (SUSY)[17] which is often associated with the search for dark matter and adds a wide range of different particles. In the search for dark matter one would for example look for missing transverse momentum in top quark interactions or look for resonance with the so-called two Higgs doublet models.

Another way of looking for new physics is by using simplified Models. Here one takes a well-defined model in order to describe some aspects or specific phenomenon of the UV theory. Again a good example comes from dark matter physics the beautifully named neutralino in minimal supersymmetric standard model (MSSM)[18] with MSSM being a low energy model of the SUSY. Here the neutralinos are electrically neutral fermions with a mass over 300 GeV and conserves the hypothetical R-parity in MSSM. Compared to the model specific search the result would give evidence only for the R-parity and the neutralino but not for other aspects of SUSY.

These first two methods depend entirely on a theoretical model. Granted these models are often well motivated by known physics or mathematical structures. But history has shown multiple times that experiments can produce unexpected results. As a recent example being the accelerating expansion of the universe by some so-called dark energy. Unexpected results are often not described by existing models, therefore a model independent search has to be done and EFT is the primary tool for this in particle physics. Taking a look at the Fermi theory (section 3.1.1) again one will realize that Fermi's theory was able to approximate the weak interaction but isn't able to describe the structure of weak interactions. Only using Fermi's theory one would not be able to describe CP-Violation. Generally describing an exotic interaction using EFT one can only predict low order processes, but the low energy observer can't make predicting as to what he is actually describing. The results can then be used to construct an appropriate model or match an existing one and use the first two methods to validate this model.

The search for on shell particles where the energy and momentum of the decay products add up the particle mass is called a direct search. In EFT the researched virtual particle is off shell and therefore doesn't appear in the final state. This is called indirect search. In figure 3.4a model one would be a candidate for a direct search while model two is candidate for an indirect search using EFT.

3.3 Vector Boson Scattering

Vector Boson Scattering (VBS)[19] refers to the scattering of any electroweak gauge Boson $V=W^\pm, Z, \gamma$. This definition includes diboson processes which makes it necessary to specify the final state for VBS and diboson processes. The VBS final state $VVjj$ is characterized by the two bosons and two jets while diboson processes final state only contains two bosons VV in the final state. Since gauge bosons have a short half-life of $3 \cdot 10^{-25}\text{s}$ one needs to include the decay of the outgoing boson leading to the full process $qq \rightarrow VVjj \rightarrow 4ljj$ shown in figure 3.6. In leading order only quark-initiated diagrams produce vector bosons. These

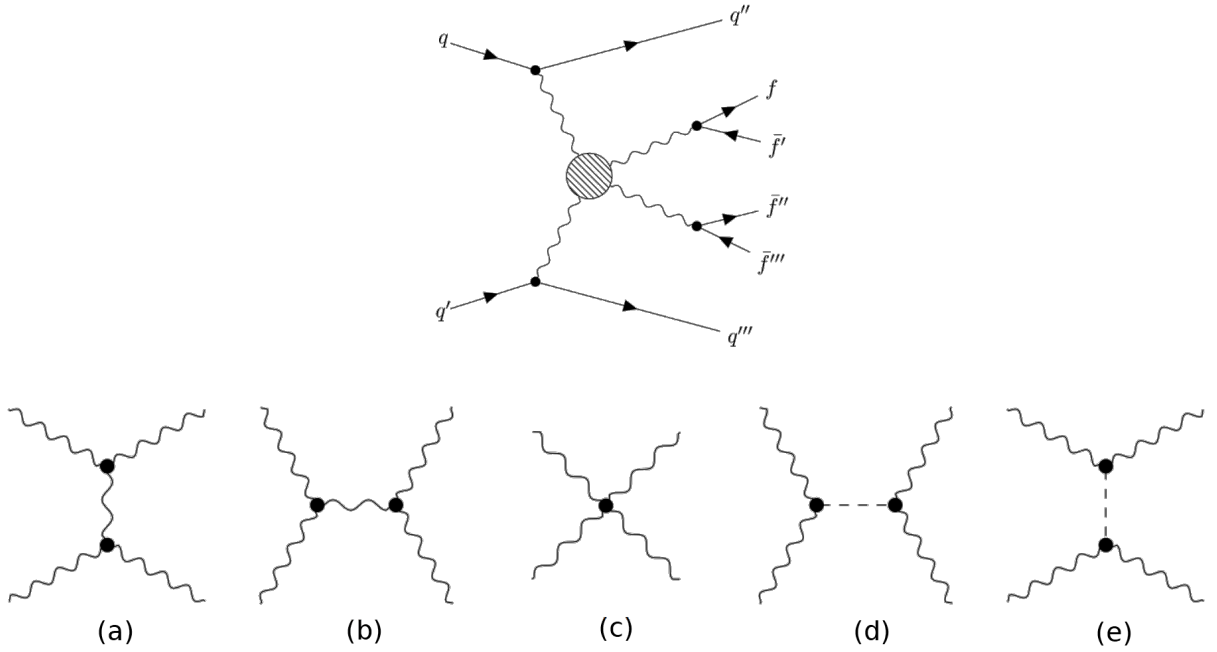


Figure 3.6: Structure of full VBS process $qq \rightarrow VVjj \rightarrow 4ljj$ with two of the four leptons having a charge. The circle stands for the processes a to e which come from the non-Abelian gauge group $SU(2)$ for weak interactions in leading order $VV \rightarrow VV$ processes.[19]

quarks are shifted by a small angle away from the beam axis resulting in the for the VBS process characteristic tagging jets. The couplings a to e in 3.6 are all electroweak interactions and based on there coupling structure produce a squared matrix element $|M^2| \propto \alpha_{EW}^6$. The α_{EW} stands for the combined coupling strength of the electroweak and electromagnetic interactions. These couplings can also be achieved by coupling structure $|M^2| \propto \alpha_{EW}^4 \alpha_S^2$, but these couplings however do not contribute to VBS processes. In the signal for VBS processes the diagrams with less than six electroweak diagrams are considered as background defining the $VVjj - EW6$ processes. Some examples for the these processes can be seen in 3.7. How these processes are selected will be discussed in the following chapter. The $W^\pm Z$ processes is dominated by EW and QCD interactions specifically the EFT Terms are only accounted for in the EW interactions.

Multiple factors make the study of VBS processes interesting. VBS processes are only accessible from LHC Run-II and forward making them more relevant in the future. The appearance of both TGC and QGC lead to interesting studies of polarization, gauge invariance, unitarity and Higgs physics. The distinct two jet finale state makes the selection of VBS process relatively easy leading to a small background estimation. In BSM both properties are relevant as new models often include TGC and QGC. Without knowing the underlying theory it is hard to make predictions on the impact of a BSM theory on the background. In EFT TGC are essential for analysis on dim-6 operates and QGC for studying dim-8 operators. The accessibility of a variety of couplings and the fact that no BSM theory to date fully describes anomalous couplings motivate the research on resonances in VBS using EFT.

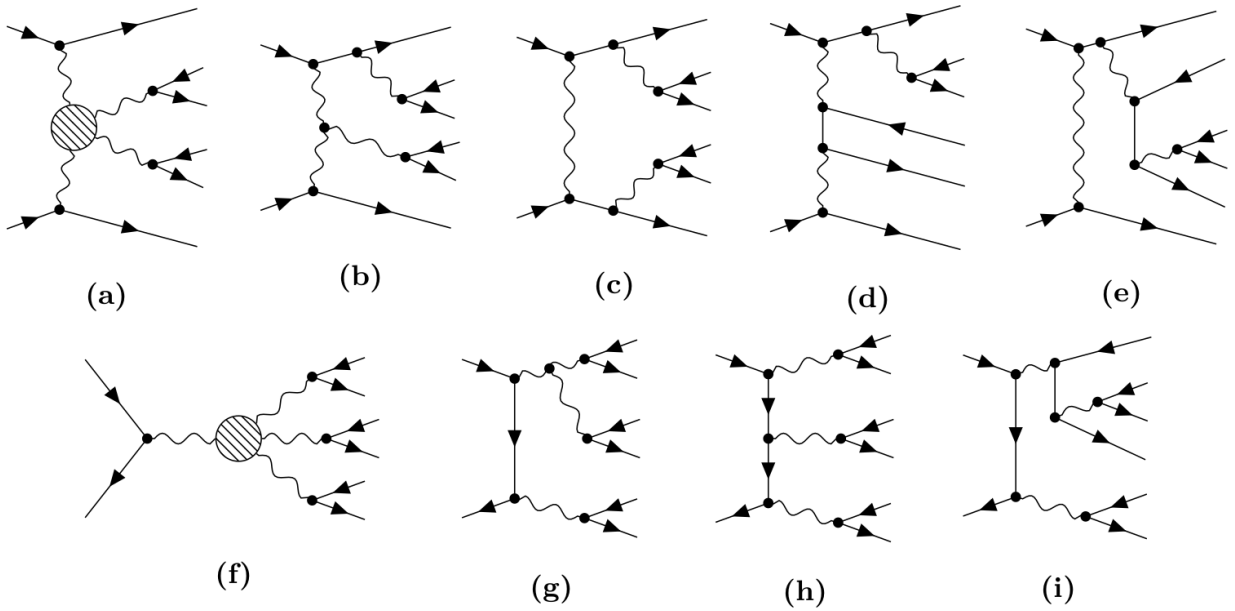


Figure 3.7: Example Feynman diagrams for VVjj-EW6 processes. The dashed circle stands for the Feynman diagrams a-e in Figure 3.6

4 Event Selection and Statistical Method

4.1 Event selection

Event selection is done in order to decrease background and get a clean signal process. VBS processes have a small cross-section around 1 fb resulting in a small event count. In the 2015 and 2016 Atlas run with 36 fb^{-1} not even 100 events produce VBS processes. Therefore, one has to carefully select Events in order to get a meaningful signal process. The event selection is implemented as described in [19] using the Common Analysis Framework(CAF)[20]. The object selection however was already done in ELCore and account for the event cleaning, GoodRunList, Trigger, Primary Vertex in Table 4.1 these can't be change in the CAF. Therefore, only the event selection done in the CAF will be discussed. ELCore produces beam reconstruction level samples. The event selection in the CAF is split into the three phase space regions llvjj, WZjj and the VBS signal region(VBSSR). Even though the regions are different the selection criteria overlap. The WZjj region use the selection criteria of the llvjj as base and introduces new selection criteria. The same is true for the VBSSR which builds upon the WZjj region as show in Table 4.1.

llvjj region: Only events with 3 or more leptons that pass the Z-analysis are chosen. The leptons are then assigned to the decaying gauge boson. For this same flavour and opposite charge(SFOC) leptons pairs are chosen. The pair with invariant mass close to the Z boson mass is assigned to the Z boson. The highest transverse momentum p_T lepton from the remaining leptons is assigned to the $W^\pm$ boson and required to pass the W-analysis. Chosen leptons need a transverse momentum $p_T > 25(27)$ GeV for the 2015(2016) campaign for the events to pass the trigger threshold. Events have to have two or more events in order to be selected. These jets need to have $p_T(j) > 40$ GeV to be considered as tagging jets.

WZjj region: Additional cuts are applied for the WZjj region in order to maximize $W^\pm Z$ contribution in the llvjj final state. Some events in ZZ diboson production are expected to produce an additional lepton therefore a four lepton baseline veto is applied. Events where the jet is considered a b-jet are discarded to minimize $t\bar{t}$ and other t-quark contributions. The

transverse mass of the $W^\pm$ boson is required to be greater than $M_T(W) > 30$ GeV. The Z lepton pair has to have an invariant mass within 10 GeV of the Z boson mass $m_Z = 91.1876$.

VBSSR region: The resonance fitting is done in the VBSSR region. For this additional requirements must be added increasing WZjj-EW6 contribution compared to WZjj-EW4 and WZjj-EW5. For this two cuts for the tagging jets have to be added. The invariant mass must be $M(jj) > 500$ GeV and the absolute rapidity difference has to be constraint $\Delta Y(jj) > 2$.

Figure 4.1 shows the cuts for the VBSSR region applied for the combined data from mc16d and mc16e with a combined luminosity of 102.7 fb^{-1} . These histograms will be combined to WZ + Background in the following plots. Ideally one would use all campaigns mc16a, mc16d and mc16e with combined luminosity of 139 fb^{-1} to achieve the best statistic. This however is currently not possible due to limits in CAF.

Event selection criterion	llvjj region	WZjj region	VBSSR
Event cleaning	✓	✓	✓
GoodRunList	✓	✓	✓
Trigger	✓	✓	✓
Primary Vertex	✓	✓	✓
llvjj finale state			
≥ 2 jets	✓	✓	✓
≥ 3 Z-Analysis leptons	✓	✓	✓
One SFOC pair	✓	✓	✓
l_W is in W-Analysis selection	✓	✓	✓
Transverse momentum of leading leptons			
$p_T(l) > 25(27) \text{ GeV}$	✓	✓	✓
Transverse momentum of subleading jet			
$p_T(j_2) > 40 \text{ GeV}$	✓	✓	✓
$M_T(W) > 30 \text{ GeV}$		✓	✓
$ M(ll) - 91.1876 \text{ GeV} < 10 \text{ GeV}$		✓	✓
four Baseline leptons veto		✓	✓
b-jet veto		✓	✓
$M(jj) > 500 \text{ GeV}$			✓
$\Delta Y(jj) > 2$			✓

Table 4.1: Schematic view of cuts applied in different phase space regions. [19]

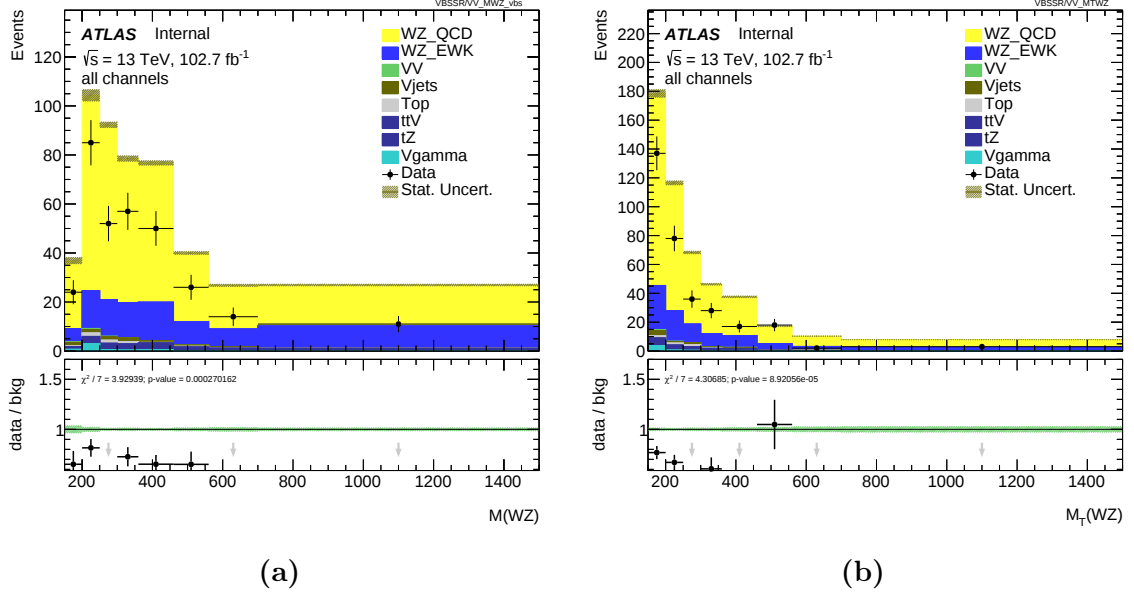


Figure 4.1: VBSSR region for a) invariant mass, b) transverse mass. Showing reproduction of SM as well as the in section 3.3 discussed dominance of QCD and EW processes. VV, Vjets, Top, ttV, Vgamma, WZ_EWK , WZ_QCD are combined to ' $WZ_SM + Background$ ' in later plots. For the fits WZ_EWK is used as signal.

In order to get a valid result the SM limits have to be reproduced. The samples used for this thesis were already produced before starting the thesis and no samples were produced specifically for this thesis. Therefore, samples used for the analysis did not use the same settings as the samples used for the SM limit setting([21],[22]) resulting in differences in the number of events in tabular 4.2. The EFT limits for the SM for the ATLAS detector only use mc16a data while this analysis uses mc16d and mc16e data resulting in smaller limits since more data is used. The limit comparison is shown in tabular 4.3.

VBSSR	mc16d+mc16e	mc16a	SM
WZ QCD	356.8912 ± 2.4118	121.5475 ± 1.1721	144 ± 41
WZ EWK	91.2393 ± 0.4231	32.4363 ± 0.2522	24.9 ± 1.4
Background	27.2161 ± 2.0335	11.9691 ± 0.4701	31.1 ± 3.9
WZ SM + Background	475.3466 ± 3.2912	165.9529 ± 1.4050	200 ± 41

Table 4.2: Overview of events in VBSSR region. mc16a is compared to the [23] for the reproduction of the SM EFT Limits. While the resonance fitting is done with the mc16e+mc16d data. The differences between the mc16a and the SM is like cause by some ELCore settings since the cuts possible in the CAF tool were replicated.

Operator	EFT Optimized binning		SM Optimized Binnig
	$M(WZ)$	$M_T(WZ)$	$M_T(WZ)$
S0	[-49 , 47.4]	[-46 , 44.1]	[-78 , 78]
M0	[-9.1 , 11.5]	[-9.3 , 9.65]	[-15 , 15]
M1	[-16 , 15.7]	[-15 , 14.4]	[-23 , 23]
T0	[-0.43 , 0.457]	[-0.38 , 0.325]	[-1.4 , 1.4]
T1	[-0.82 , 0.713]	[-0.72 , 0.682]	[-0.97 , 0.97]
T2	[-2.4 , 2.16]	[-2.2 , 1.96]	[-2.8 , 2.8]

Table 4.3: Asmiov fit limits for SM data with 95% CL. Differences arise from the use of mc16e, mc16d data compared to the mc16a data and the use of a BSM search optimized binning [150,200,250,300,360,460,560,700,1500] compared to the SM optimized binning [150,200,250,300,400,1500] used in [23]

4.2 Maximum Likelihood Method

In order to achieve a scientifically relevant result a statistical framework that fits the analysis has to be used. The maximum likelihood method builds the base of the statistics used. [24], [25] and [26] provide an in depth view into the topic, but a short introduction is given here to understand the fitting results. The maximum likelihood method takes observed data and an assumed probability distribution in order to give the best estimate for a parameter.

The likelihood function for a joint probability distribution(pdf) is defined as:

$$L(\vec{x}, \vec{\Theta}) = \prod_{i=1}^n f(x_i, \vec{\Theta}) \quad (4.1)$$

With distribution $f(x; \vec{\Theta})$, $\vec{\Theta} = (\Theta_1, \Theta_2, \dots, \Theta_m)$ and a measurement of n independent values $\vec{x} = (x_1, x_2, \dots, x_n)$. The maximum of the likelihood function is the best estimate for the parameter $\vec{\Theta}$. It is often the case in particle physics to maximize the log-Likelihood function $\ln L$. The derivative can be written as follows since the logarithm is a monotonically increasing function.

$$\left. \frac{\partial L}{\partial \Theta_i} \right|_{\vec{\Theta}=\hat{\Theta}} = 0 \quad \implies \quad \left. \frac{\partial \ln L}{\partial \Theta_i} \right|_{\vec{\Theta}=\hat{\Theta}} = 0 \quad (4.2)$$

Where $\hat{\Theta}$ is the maximum likelihood estimate. This can be applied to a Gaussian distribution with $E[x_i] = \mu(y_i, \vec{\Theta})$ and $V[x_i] = \sigma_i^2$

$$f(x, \vec{\Theta}) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu(y_i, \vec{\Theta}))^2}{2\sigma^2}} \quad (4.3)$$

resulting in a log-Likelihood function

$$\ln L(\vec{\Theta}) = \sum_{i=1}^n \left(\ln \frac{1}{\sqrt{2\pi}} - \ln \sigma - \frac{(x_i - \mu(y_i, \vec{\Theta}))^2}{2\sigma^2} \right) \quad (4.4)$$

Only μ is dependent in the parameter on $\vec{\Theta}$ and therefore only the third term is relevant. One can now compare the result to the chi-squared method.

$$\chi^2(\vec{\Theta}) = \sum_{i=1}^n \frac{(x_i - \mu(y_i, \vec{\Theta}))^2}{\sigma^2} \quad (4.5)$$

The log-likelihood function can therefore be written as $-2\ln L = \chi^2$. If x_i is not a Gaussian distribution than the chi-squared method is an "ad hoc" method. This form has the advantage that if a Gaussian distribution is assumed the parameters can be easily determined but can give asymmetric uncertainties. The standard deviation can be calculated by setting the derivative of L with respect to σ and derivative of L with respect to μ equal to zero.

$$\frac{\partial \ln L}{\partial \mu} = \sum_{i=1}^n \frac{x_i - \mu}{\sigma^2} = 0 \quad (4.6)$$

$$\frac{\partial \ln L}{\partial \sigma} = \sum_{i=1}^n \frac{(x_i - \mu)^2}{\sigma^3} - \frac{1}{\sigma} = 0 \quad (4.7)$$

These two equations can now be solved simultaneously leading to

$$\mu = \frac{1}{N} \sum_{i=1}^N x_i = \bar{x} \quad \text{and} \quad \sigma^2 = \frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2 = n. \quad (4.8)$$

With this the one sigma and two sigma environment can be calculated for a negative log-likelihood function as $1\sigma = 1$ and $2\sigma = 4$ [27]

4.3 Likelihood ratio test

The likelihood-ratio test[28] is used to estimate the goodness of fit based on their likelihoods. In general the denominator contains the likelihood for the entire parameter space, while numerator introduces constraints on the parameter space.

$$\lambda(\epsilon) = \frac{L(\epsilon, \hat{\Theta}_0)}{L(\hat{\epsilon}, \hat{\Theta})} \quad (4.9)$$

where $\hat{\vec{\Theta}}$ donates the value $\vec{\Theta}$ for which L is maximized for a given ϵ . ϵ is the conditional maximum-likelihood estimator of $\vec{\Theta}$. $\hat{\epsilon}$ and $\hat{\Theta}$ are the maximum likelihood estimators for the unconditional likelihood. In case of the log-likelihood function this can be written as:

$$-2\lambda = -2\ln\left(\frac{L(A)}{L(B)}\right) = -2(\ln L(A) - \ln L(B)) = -2\Delta L \quad (4.10)$$

In the context of fitting in EFT $L(A)$ donates a fixed parameter while $L(B)$ donates the floating parameter. The likelihood-ratio is than plotted against the parameter values 5.2.

5 Results

The EFT samples for each parameter S_0 , M_0 , M_1 , T_0 , T_1 , T_2 are fitted against the combined SM and GM Resonance data. It is assumed that the coefficients are only affected by anomalous QGC (aQGC) couplings. Only one coefficient is fitted at once while the other coefficients are set to zero. As discussed in section 3.1 good fits are expected for sufficiently high resonance mass. The fit can not identify small energies or high energy with small cross-sections resonances as shown in 5.1¹.

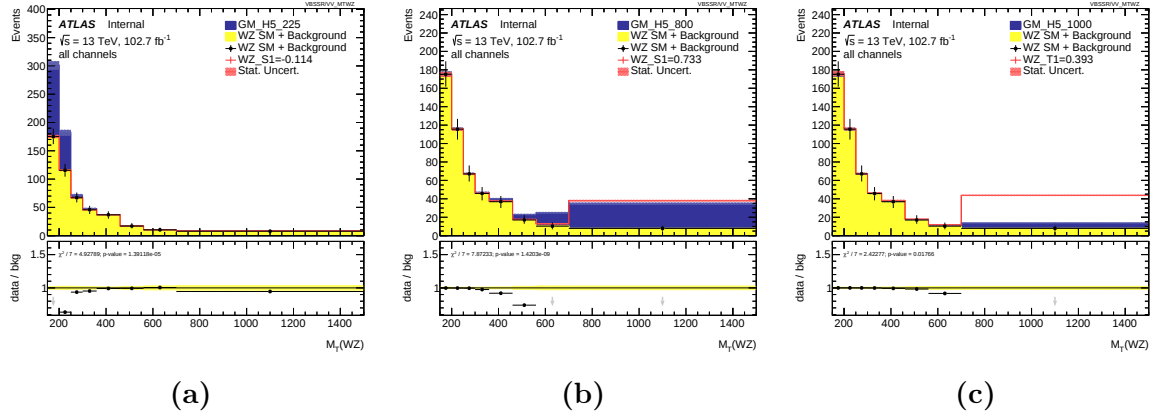


Figure 5.1: a) The mass of the resonance has approximately the same energy as the WZ peak but for the WZ peak the EFT prediction should be the SM therefore EFT can not describe the 225 GeV Resonance and the coefficient fit diverges. b) 800 GeV has a high cross-section and the energy is in the region where SM and EFT deviate therefore the coefficients can be fitted accurately. c) 1000 GeV the cross-section is too low the fit can not produce a significant result even though the resonance is in the right energy region.

Evaluating which fit is good can be done qualitative by simply looking at the invariant mass plots if the EFT sample scaled with the best fit value is able to describe the resonance one can argue that the fit is good. But this is not accurately possible for resonances peaks that are higher energy than the $W^\pm Z$ peak, but the start of the peak is still part of the $W^\pm Z$ peak.

For a quantitative analysis the significance quotient has to be calculated from the likelihood ratio $f(\mu) = -2\Delta\log(L)$ where μ is the signal strength. The significance [28] can be calculated using $Z(\mu) = \sqrt{f(\mu)}$ resulting in $S = \frac{Z_{GM}(0)}{Z_{EFT}(0)}$. Here Z_{GM} is the significance when the GM sample is used as coefficient in EFTFun [29] and fitted with SM as measurement and as

¹Technical reasons cause the ratio plot to display the wrong errors

prediction. The Z_{EFT} is the fit of an EFT coefficient for the SM combined with the GM model as measurement against the SM as prediction. $f(0)$ can be interpreted as the difference to the SM, if $f(0) = 0$ only the SM was measured. If $f(0) > 0$ there is an EFT, GM which is more likely than the SM. For $f(0) > 4$ the SM is excluded. The value of $\mu = 0$ can be read off from the log-likelihood ratio plot in 5.2. The scale is dependent on the operator as well as the allowed range making it difficult to estimate a read off error. The error can be minimized by looking at positive and negative extrema and limiting the range to zero as well as the shape including both extrema. Since the likelihood-function is continuous all plots give the same $f(0)$ value. All three ranges should be used in case only one extremum exists, or only one is recognized by the fit this is often the case for low energy resonances. Using this the error becomes small compared to the statistical errors. All EFT coefficients in 5.3 with $S > 0.8$ are able to reproduce the statistical significance of the GM model to more than 80% certainty.

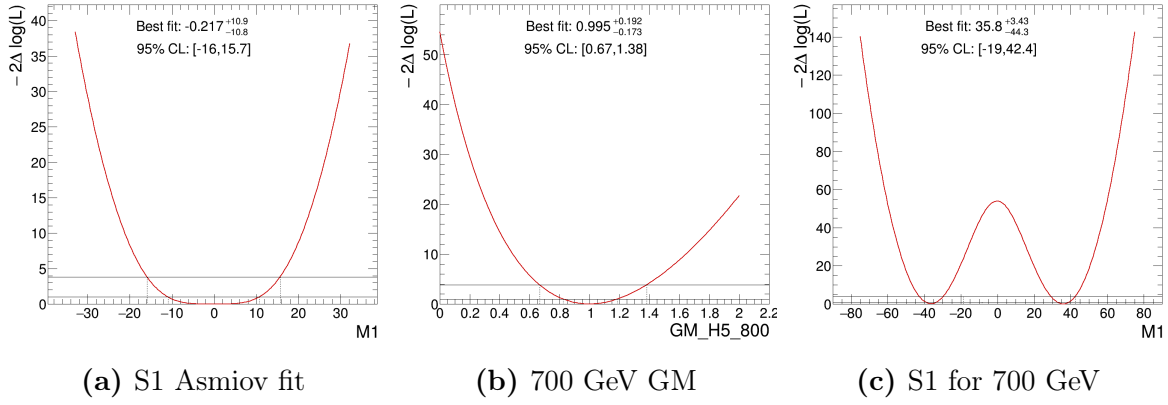


Figure 5.2: a) The best fit value is zero since the SM is reproduced in the Asimov fit. b) The GM model is used as coefficient. c) The SM is excluded, and two extrema emerge from the inclusion of the quadratic operator term.

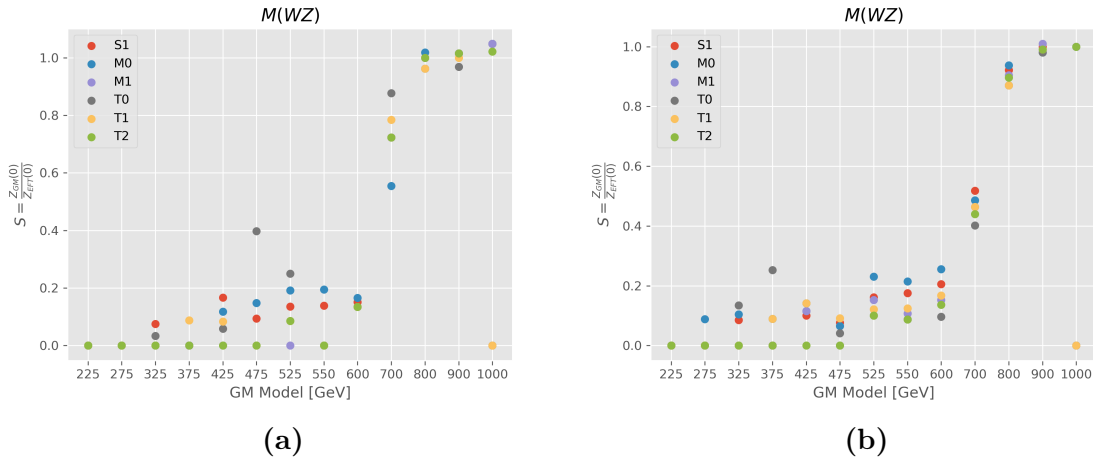


Figure 5.3: a) EFT coefficients significance for invariant Mass b) EFT coefficients significance for transverse Mass. Plots for all operators individually are shown in appendix 8.1

The result is independent of the resonance cross-section. This can be shown by scaling the resonance, in 5.4 the cross-section is scaled with 2 and 0.5 which results in equal significance compared to the non-scaled resonances. The cross-section can not be scaled higher without breaking the fitting-tool as the values get unreasonably high. In the plots with 0.5 times the cross-section, the cross-section becomes too low to be picked up by the fitting tool. This happens for both the $M(WZ)$ and the $M_T(WZ)$ for the 1000 GeV resonance and the $M_T(WZ)$ for 900 GeV. Which suggests that the $M(WZ)$ will give a more accurate result for low cross-section measurements.



Figure 5.4: **a)** EFT coefficients significance for invariant Mass **b)** EFT coefficients significance for transverse Mass. The comparison for all operators is shown in 8.2

The 700 GeV sample has a significance of 0.7–0.8 making it irrelevant for this analysis but with the high dependence on the binning one may be able to get a significant result by optimizing the binning. The EFT limits for relevant resonance masses are shown in tabular 5.1. The limits for both extrema should be equivalent but the EFTFun only expects one extremum when fitting and therefore includes the second extremum in the 95%CL if the second extremum is too close to the first extremum. In order to find both extrema the range from a minimal range to zero for the negative extremum and from zero to a positive minimal range. The minimal range should leave space for the fit to find the best fit value. T0 doesn't show this behaviour which is likely caused by the larger uncertainties shown in 5.5 and 5.6. A full set of all parameters and both invariant mass and transverse mass are shown in 5.5 and 5.6 for an 800 GeV resonance as this is the resonance with the lowest energy and statistical significance. Other significant resonances are shown in the appendix 8.3. For the 1000 GeV resonance the coefficients T1, T0 in the invariant mass plot as well as M0, T0, T1 in the transverse mass plots could not be fitted as the cross-section is too small.

Mass	$M(WZ)$					
	S1	M0	M1	T0	T1	T2
positive extrema						
800 GeV	[89,129]	[20,28.4]	[29,42.4]	[2.1,2.8]	[1.4,2.01]	[4.1,6.03]
900 GeV	[-10,76.8]	[1.1,17.2]	[-0.41,25.3]	no extrema	[-0.057,1.18]	[0.035,3.56]
1000 GeV	[-447,71.7]	[281,16.2]	[-207,23.6]	no extrema	[-0.5,1.1]	[-8.2,3.32]
negative extrema						
800 GeV	[-130,-90.4]	[-27,-18.4]	[-43,-29.6]	[-1.9,-1.11]	[-2.1,-1.48]	[-6.3,-4.37]
900 GeV	[-78,248]	[-16,-0.115]	[-26,0.329]	[-0.89,0.109]	[-1.3,0.0591]	[-3.8,0.186]
1000 GeV	[-73,1096]	[-15,5.52]	[-24,9.92]	[-0.81,0.231]	[-1.2,14.3]	[-3.6,1.04]

Mass	$M_T(WZ)$					
	S1	M0	M1	T0	T1	T2
positive extrema						
800 GeV	[75,113]	[16,24.2]	[24,36.2]	no extrema	[1.1,1.73]	[3.2,5.0]
900 GeV	[15,68.4]	[3.4,14.8]	[4.9,22.2]	no extrema	[0.22,1.06]	[0.6,3.06]
1000 GeV	[-19,64.7]	[220.45,14]	[-23,21]	no extrema	[-0.33,1.0]	[-0.45,2.89]
negative extrema						
800 GeV	[-115,-76.3]	[-24,-15.5]	[-36,-23.8]	[-1.5,-0.792]	[-1.5,-0.792]	[-5.2,-3.41]
900 GeV	[-70,-16.4]	[-14,-2.99]	[-22,-4.97]	[-0.77,-0.0389]	[-1.1,-0.256]	[-3.3,-0.798]
1000 GeV	[-66,78.6]	[-14,6.69]	[-21,82.6]	[-0.71,0.0189]	[-1.0,0.97]	[-3.1,37.9]

Table 5.1: Invariant mass lower and upper 95% confidence level limits for a fit with linear and quadratic operators in WZ with all other aQGC parameters set to zero

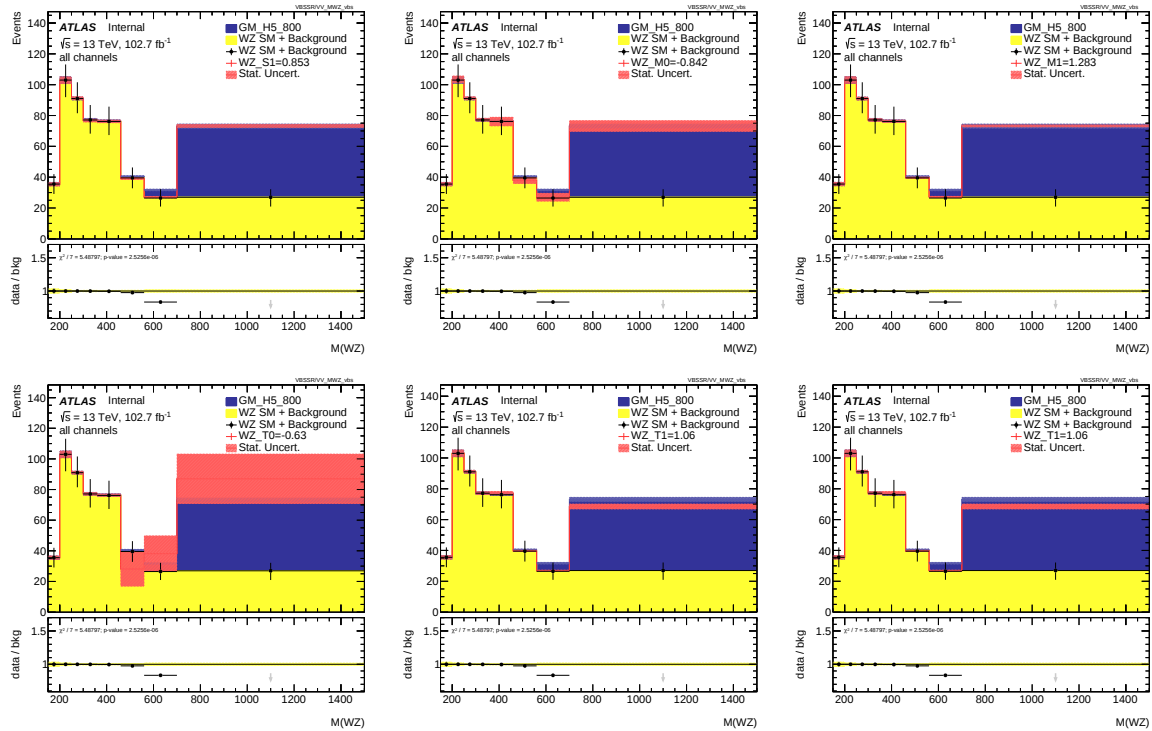


Figure 5.5: Invariant mass for coefficients S1, M0, M1, T0, T1, T2 with best fit value for 800 GeV resonance

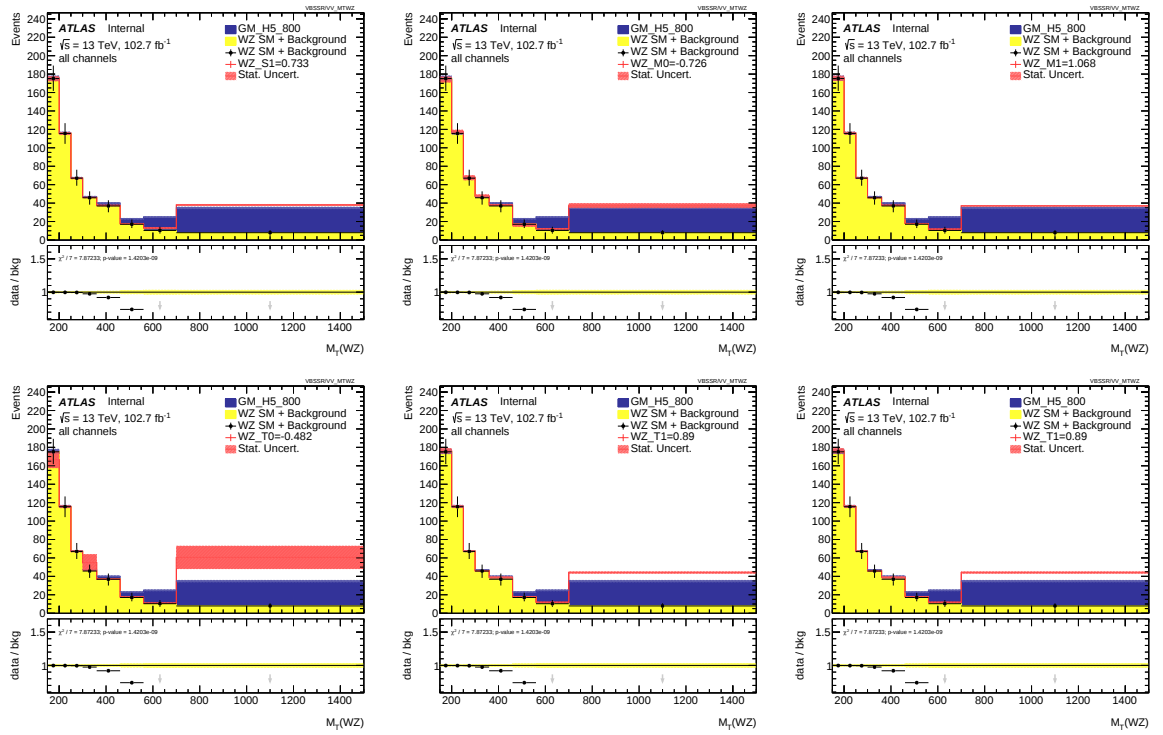


Figure 5.6: transverse mass for coefficients S1, M0, M1, T0, T1, T2 with best fit value for 800 GeV resonance

6 Summery and Outlook

In this thesis the set out goal was to find the lowest energy resonance in $W^\pm Z$ scattering process that can still be described using EFT. The results show that resonances with energy $E > 800$ GeV and an estimated minimum cross-section $\sigma_{resonance}$ of 184 ab can be described accurately. The limits for all relevant parameters S0, M0, M1, T0, T1, T2 for the research mass points with greater than 800 GeV are shown in table 5.1. These results are independent of the cross-section if the cross-section is greater than the minimum cross-section.

This result is only valid for the sensitivity of dim-8 operates in $W^\pm Z$ process, other VBS process may produce a different result. As the results are highly depend on binning further research with different binning depending on the resonance energy may be necessary since the same binning was used for all results. Only statistical uncertainties where used in this study including systematic uncertainties is needed for a more accurate prediction for the sensitivity of dim-8 operators. In this thesis dim-6 operates are assumed to be negligible or taken from another source which is often the case in EFT studies. This however may not always be true and needs further research the sensitivity of a combination of dim-6 and dim-8 operators for low energy resonances can not be predicted using these results. A next step in determining the sensitivity of dim-8 operators in VBS is to look at other VBS process which include different relevant operators. Another interesting research would be to use different models than the GM Model. Even though EFT is model independent the importance of matching the results to a BSM Model can not be overstated. Using other models will help to compare the models and if a BSM interaction is found using EFT help matching the result to a UV theory.

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Erklärung

Hiermit erkläre ich, dass ich diese Arbeit im Rahmen der Betreuung am Institut für Kern und Teilchen Physik ohne unzulässige Hilfe Dritter verfasst und alle Quellen als solche gekennzeichnet habe.

Georg Schmieder
Dresden, Mai 2022

ATLAS Preliminary
 $\sqrt{s} = 13 \text{ TeV}$

8.1 Relevance of dim-8 operators

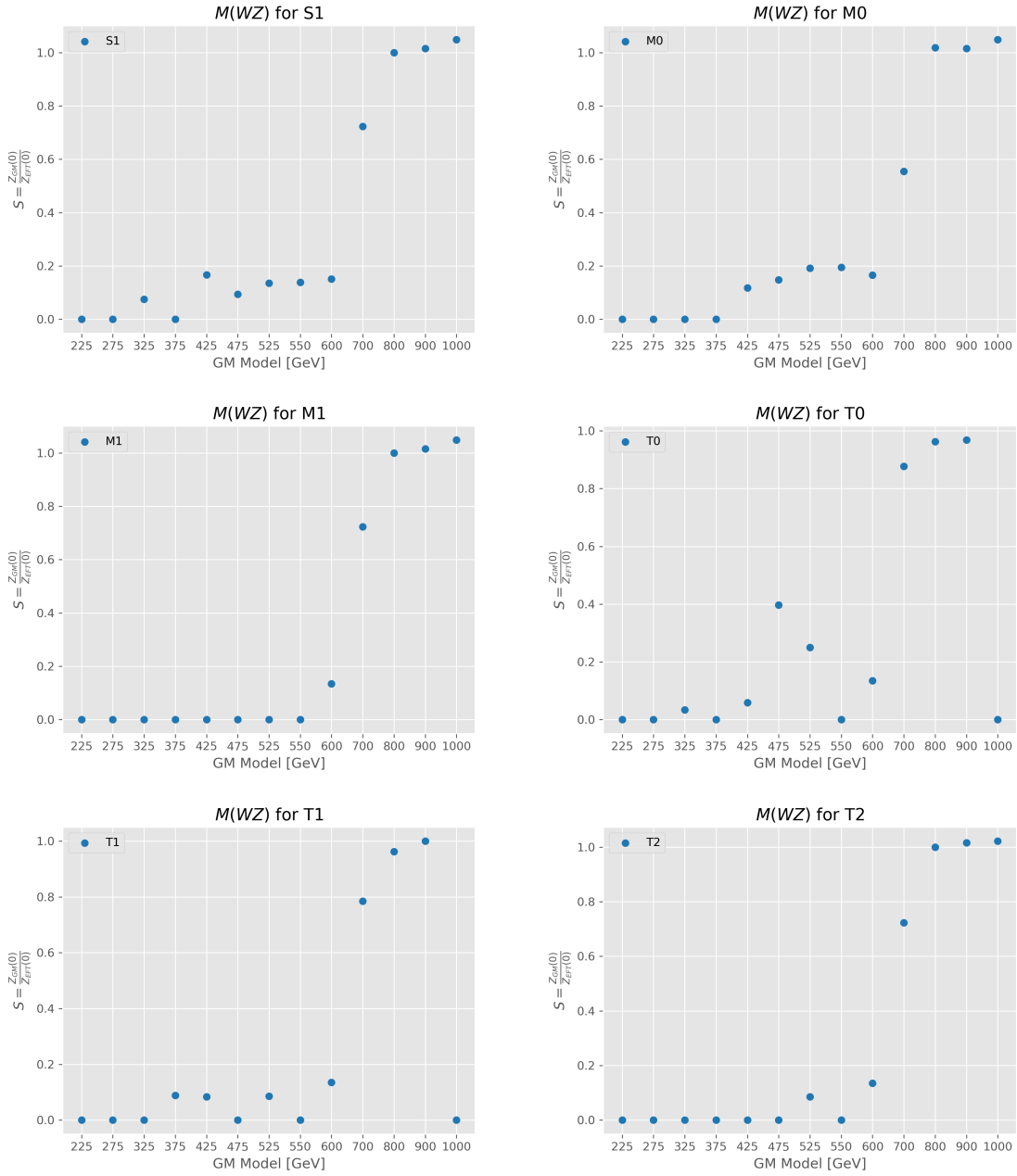


Figure 8.2: Statistical significance ratio for coefficients S1, M0, M1, T0, T1, T2 in invariant mass

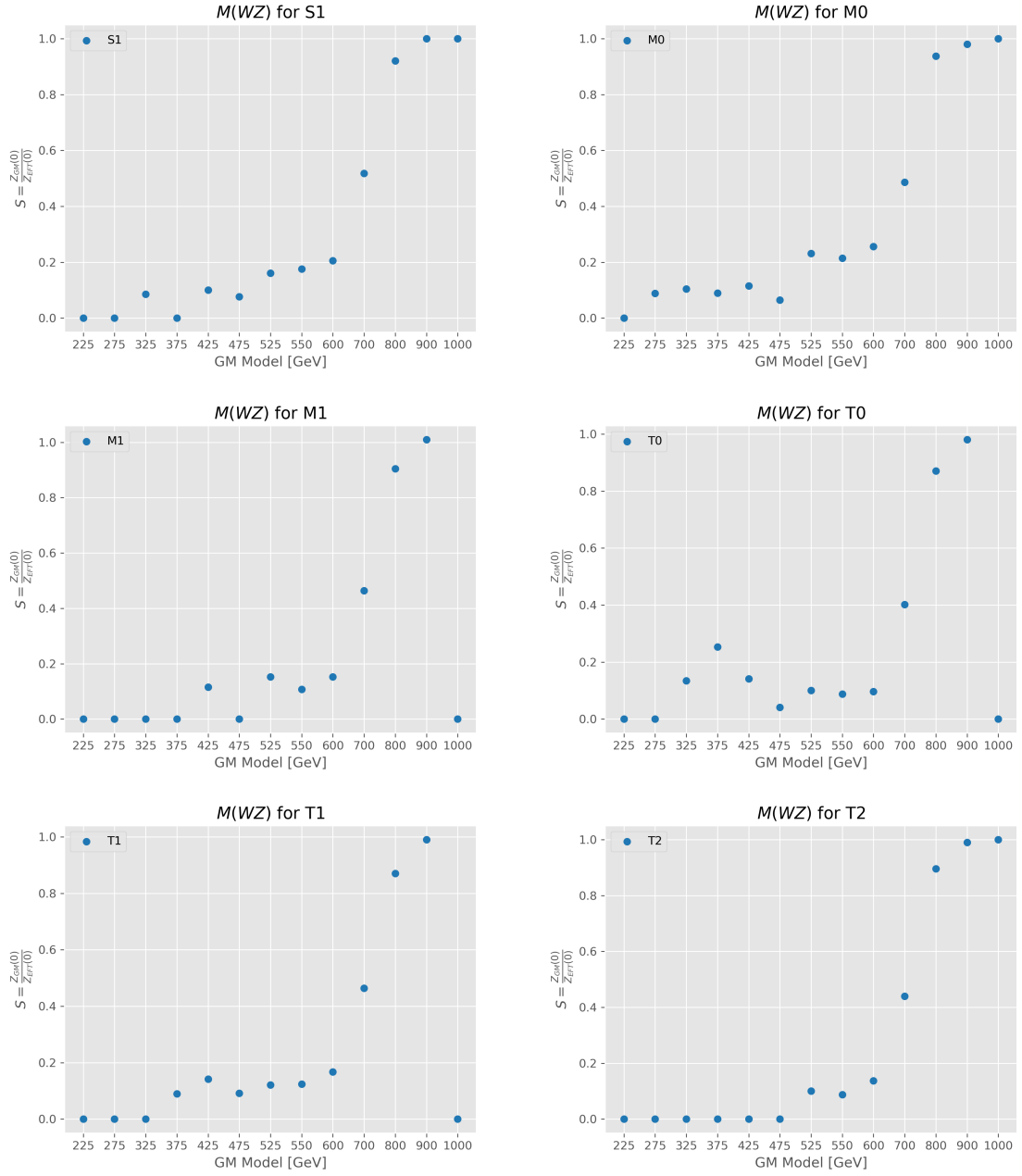


Figure 8.3: Statistical significance ratio for coefficients S1, M0, M1, T0, T1, T2 in transverse mass

8.2 Cross-section comparison for dim-8 operators

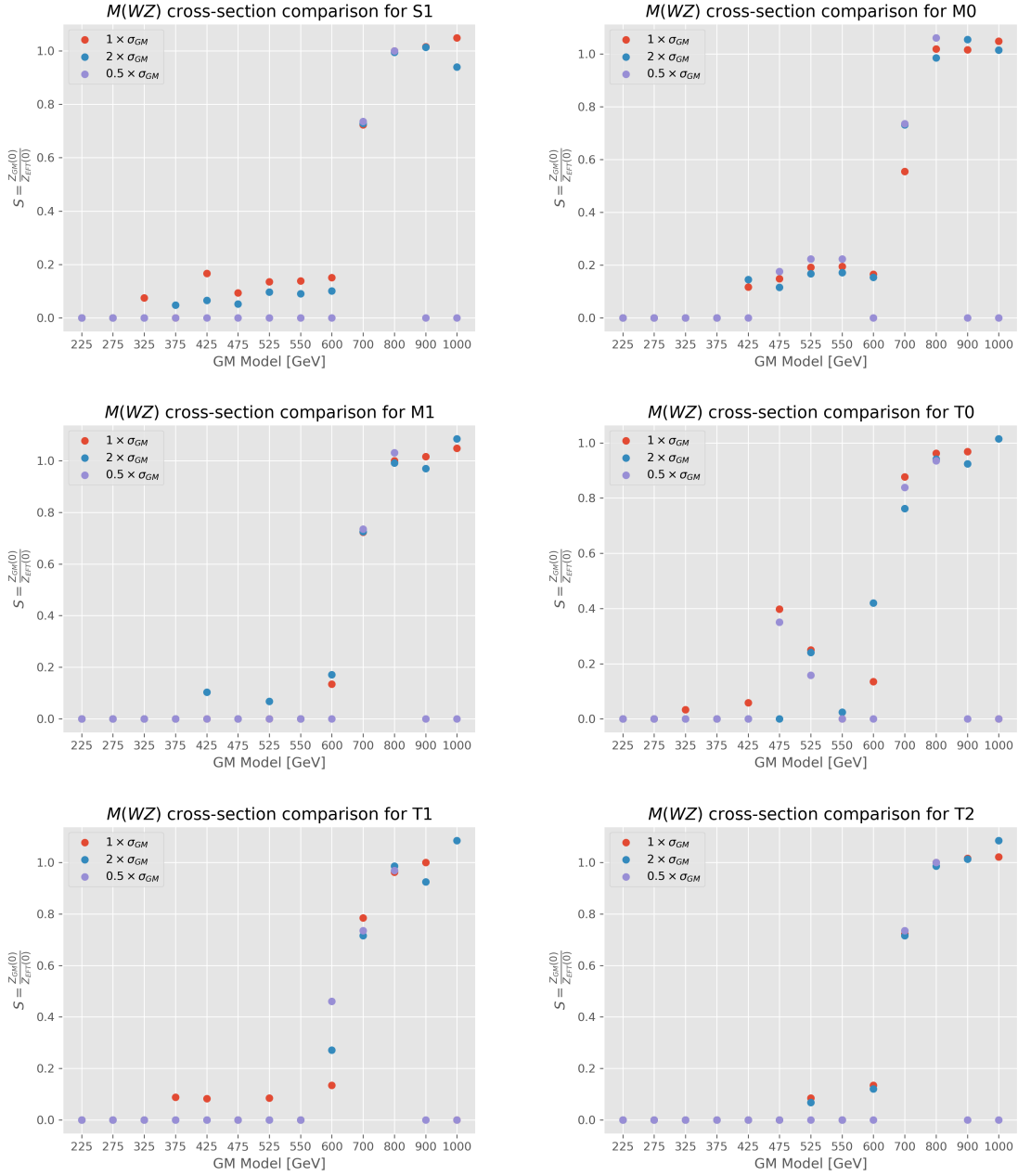


Figure 8.4: Statistical significance ratio cross-section comparison for operators coefficients S1, M0, M1, T0, T1, T2 in invariant mass

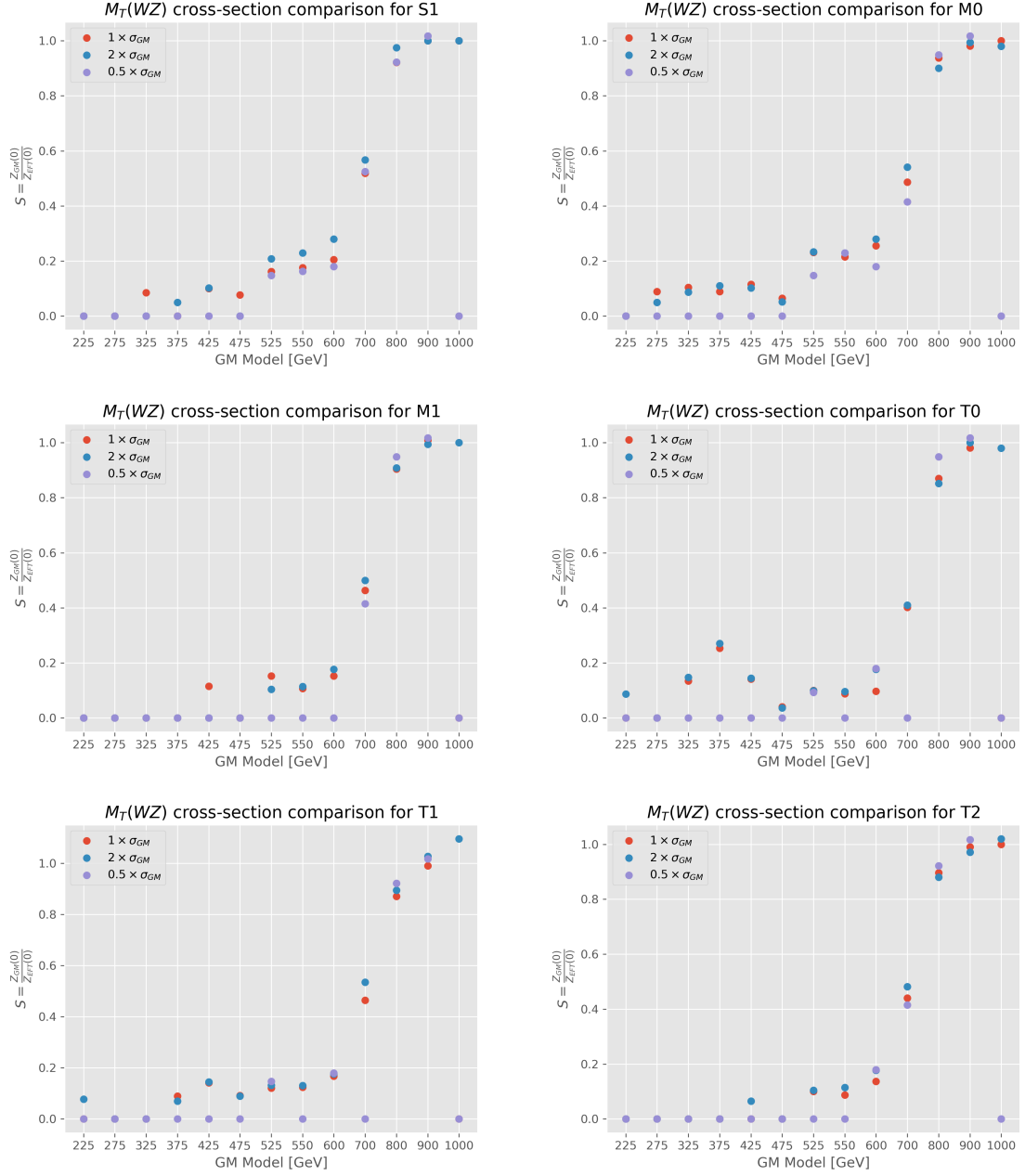


Figure 8.5: Statistical significance ratio cross-section comparison for operators coefficients S1, M0, M1, T0, T1, T2 in transverse mass

8.3 Resonances

8.3.1 900 GeV resonance

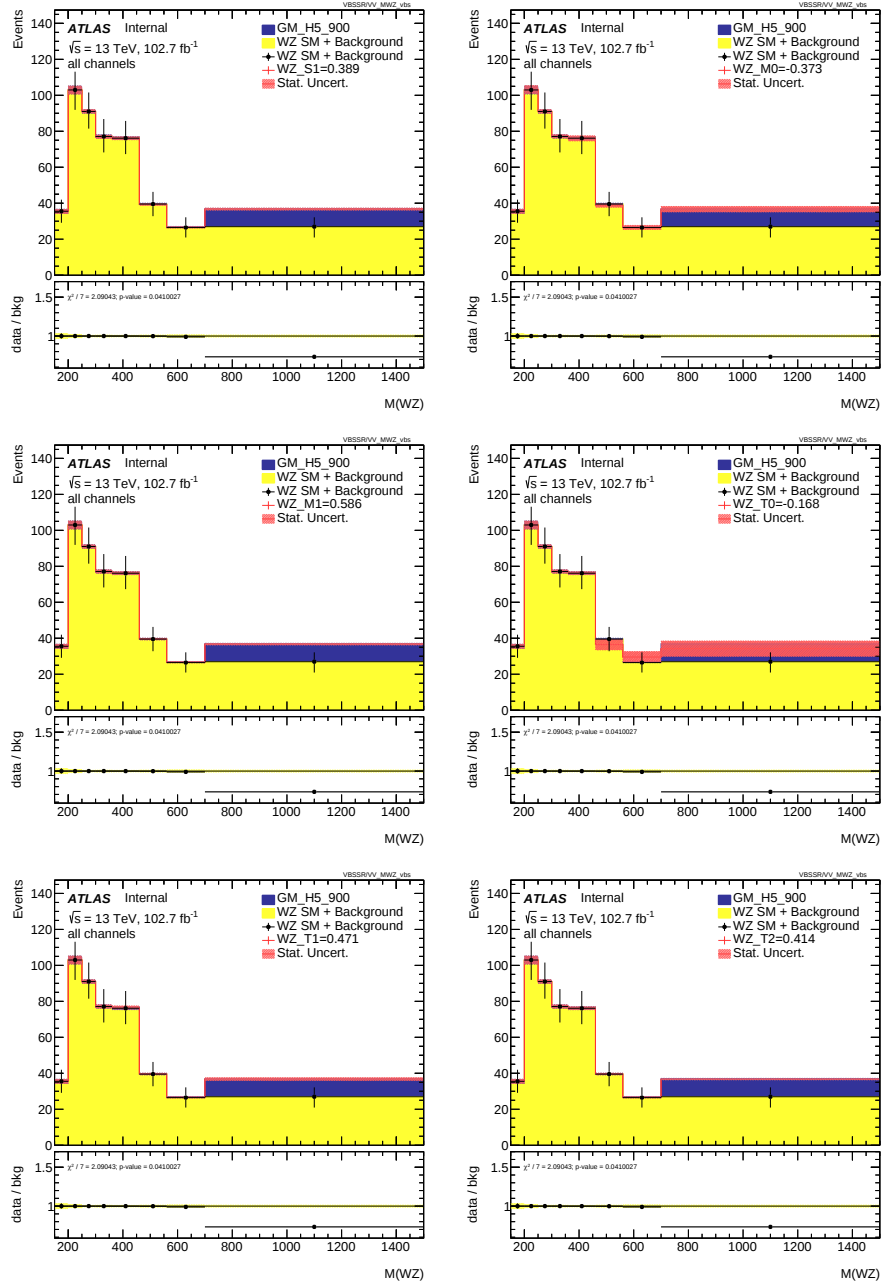


Figure 8.6: Invariant mass for parameters S1, M0, M1, T0, T1, T2 with best fit value for 900 GeV resonance

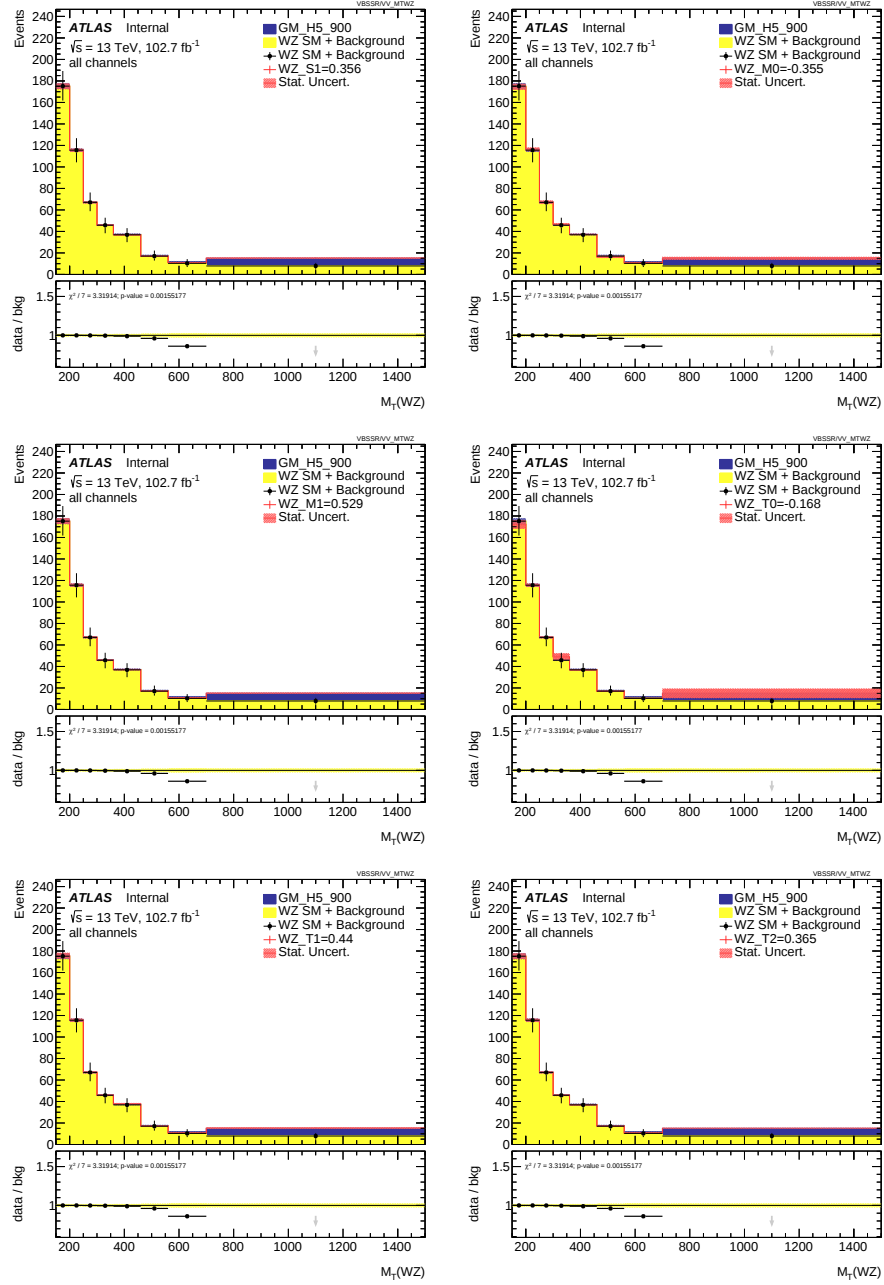


Figure 8.7: transverse mass for parameters S1, M0, M1, T0, T1, T2 with best fit value for 900 GeV resonance

8.3.2 1000 GeV resonance

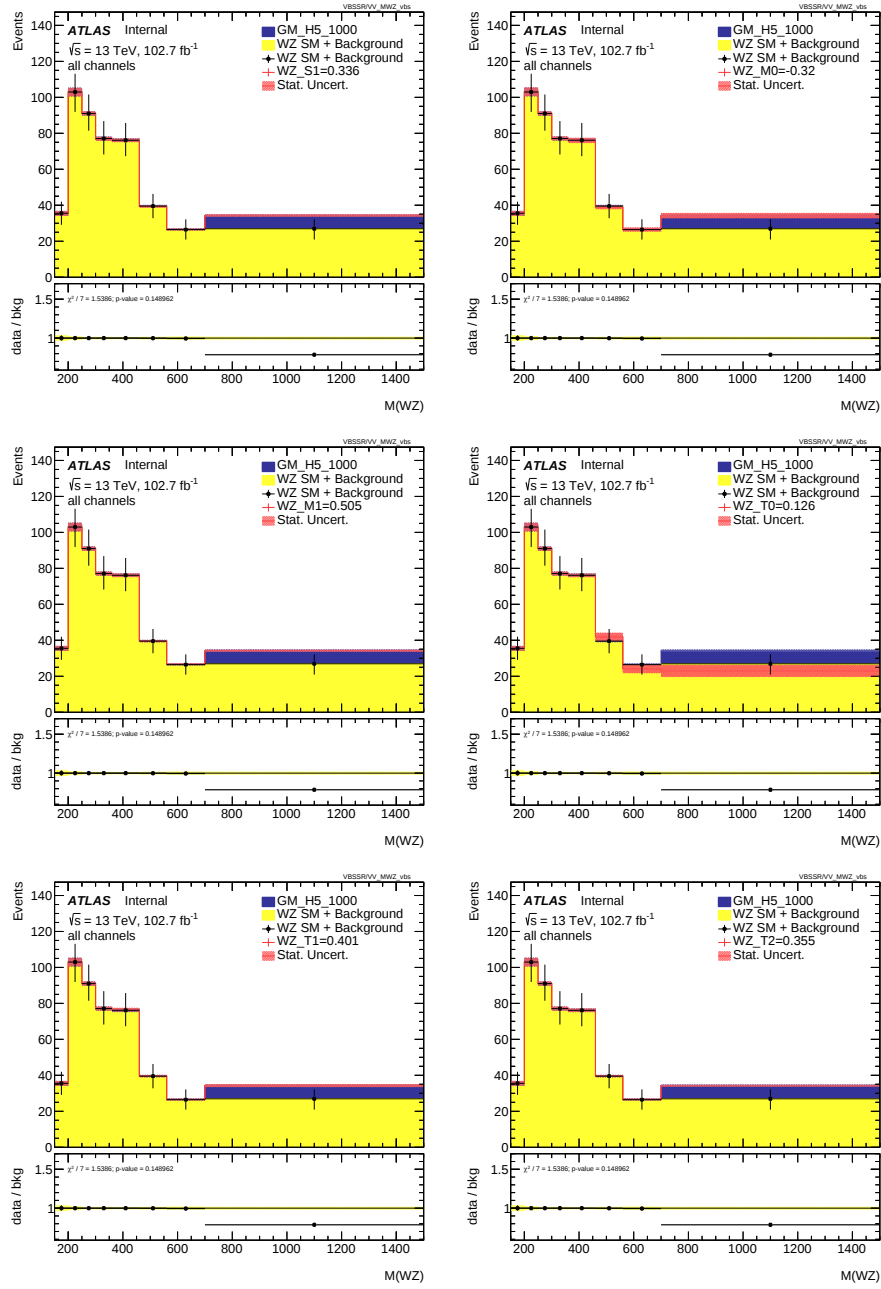


Figure 8.8: Invariant mass for parameters S1, M0, M1, T0, T1, T2 with best fit value for 1000 GeV resonance

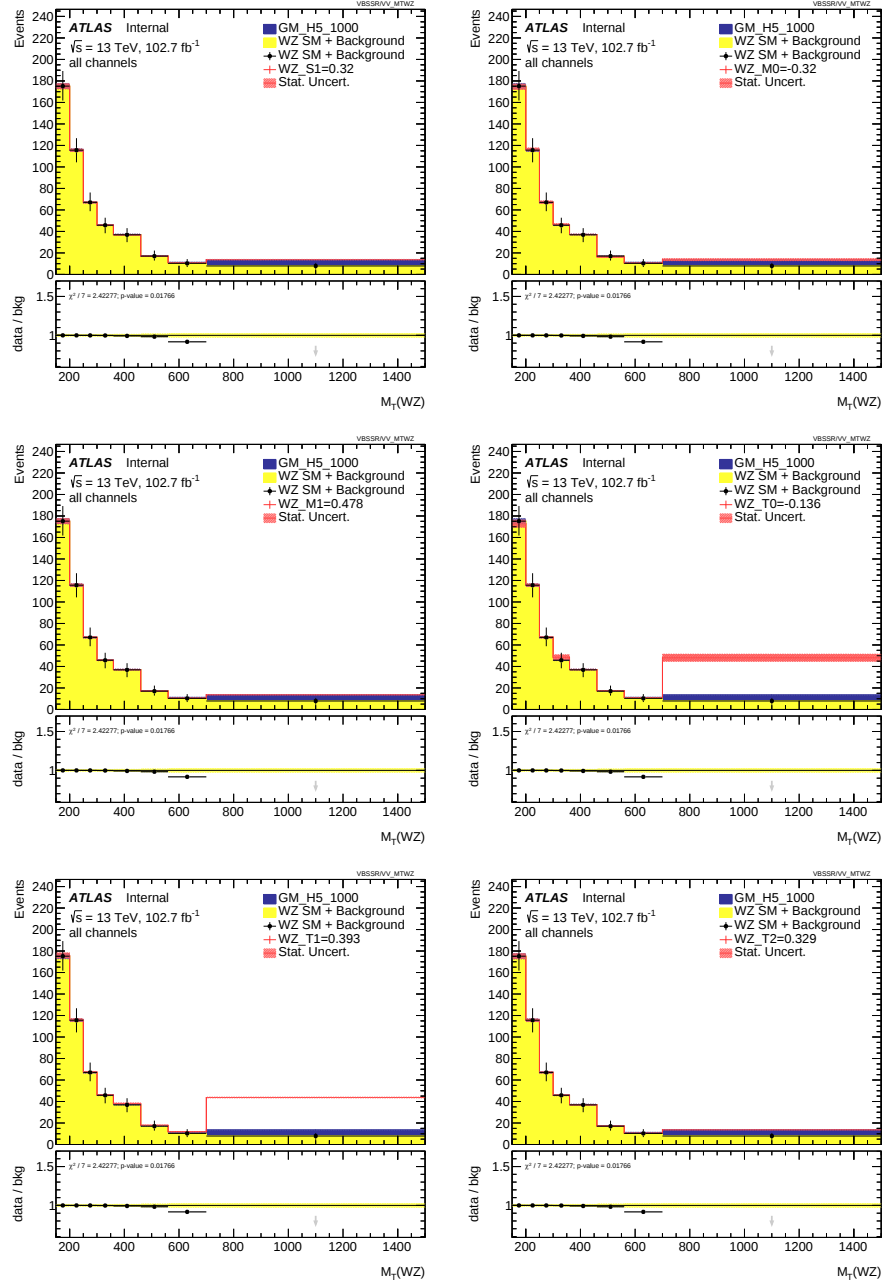


Figure 8.9: transverse mass for parameters S1, M0, M1, T0, T1, T2 with best fit value for 1000 GeV resonance