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Dipartimento di Fisica e Astronomia

Tesi di Dottorato

**Search for heavy resonances  
decaying into a  $Z$  boson and a vector  
boson in the  $\nu\bar{\nu} q\bar{q}$  final state at CMS**

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"I have no special talent. I am only passionately curious."  
(A. Einstein)



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<sup>1</sup> *Abstract*





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## 2 *Chapter 1*

### 3 *Introduction*

4 This analysis searches for signal of heavy resonances decaying into a pair of heavy vector  
5 bosons. One Z boson is identified through its invisible decay ( $\nu\nu$ ), while the other is required  
6 to decay hadronically into a pair of quarks. The final states probed by this analysis therefore  
7 consists in two quarks and two neutrinos, reconstructed as missing transverse energy (met).  
8 The hadronically decaying boson (Z, W) is reconstructed as a fat jet, whose mass is used to  
9 define the signal region. Two purity categories are exploited, based on the n-subjettiness of the  
10 fat jet.

11 The search is performed by examining the distribution of the diboson reconstructed trans-  
12 verse mass of the resonance VZ (mtVZ) for a localized excess. The shape and normalization  
13 of the main background of the analysis (V+jets) are estimated with an hybrid approach using  
14 the distribution of data in the sidebands, corrected for a function accounting for potential  
15 differences between the signal region and the sidebands, while the minor background sources  
16 are taken from simulations.

## Chapter 2

# Theoretical motivation

The Standard Model (SM) of particles represents, so far, the best available description of the particles and their interactions. It is the summation of two gauge theories: the electroweak interaction, that pictures together the weak and electromagnetic interactions, and the strong interaction, or Quantum Chromodynamics (QCD). Particles, namely quarks and leptons, are described by spin 1/2 fermions, whilst interactions are embodied by spin 1 bosons. The symmetry group of the standard model is:

$$SU_C(3) \times SU_L(2) \times U_Y(1), \quad (2.1)$$

where the first factor is related to strong interactions, whose mediators are eight gluons, whilst  $SU_L(2) \times U_Y(1)$  is the electroweak symmetry group, whose mediators are photons and  $Z$ - $W^\pm$  bosons.

In renormalizable theories, with no anomalies, all gauge bosons are expected to be massless, in contrast with our experimental knowledge (cite W-Z discovery). This kind of dilemma can be solved by introducing a new scalar particle, the Higgs boson (cite Higgs article), that can give mass to weak bosons and fermions via the spontaneous symmetry breaking mechanism.

In the last decades, Standard Model has been accurately probed by many experimental facilities (LEP, Tevatron), demonstrating an impressive agreement between theoretical predictions and experimental results. The discovery of the Higgs boson at the CERN Large Hadron Collider, measured by both CMS and ATLAS collaborations [1]- [2]- [3]- [4]- [5]- [6]- [7], represents not only an extraordinary confirmation of the model, but also the latest biggest achievement in particle physics as a whole.

## 2.1 Beyond Standard Model theories

Even though the Standard Model is the most complete picture of the universe of the particles, many questions are still left open by the model. From a phenomenological point of view, some experimental observations are not included in the theory:

- in SM, neutrinos are massless (whilst experimentally it has been confirmed to be non-zero, i.e. by the neutrino oscillation);

## 2.1 Beyond Standard Model theories

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- no candidate for the dark matter is foreseen (whilst it has been observed in cosmology);
- no fields included in the SM can explain the cosmological inflation;
- SM can not justify the matter-antimatter asymmetry.

From a purely theoretical perspective, some issues are still relevant in the formulation of the model:

- *Flavour problem.*

The Standard Model has 18 free parameters: 9 fermionic masses; 3 angular parameters in Cabibbo-Kobayashi-Maskawa matrix, plus 1 phase parameter; electromagnetic coupling  $\alpha$ ; strong coupling  $\alpha_{strong}$ ; weak coupling  $\alpha_{weak}$ ; Z mass; the mass of the Higgs boson. Such a huge number of degrees of freedom is considered as weakly predictive.

- *Unification.*

There is not a “complete” unification of strong, weak and electromagnetic interactions, since each one has its own coupling constant, behaving differently at different energy scales; not to mention the fact that gravitational interaction, completely excluded from the SM.

- *Hierarchy problem.*

From Quantum Field Theory, it is known that perturbative corrections to the mass of the scalar bosons included in the theory tend to make it increase towards the energy scale at which the considered theory is valid [cite n. 4 of master thesis]. If the Standard Model is seen as a low-mass approximation of a more general theory valid up to the Planck mass scale (i.e.,  $\approx 10^{19}$  GeV), a fine-tuning cancellation of the order of 1 over  $10^{34}$  is needed in order to protect the Higgs mass at the electroweak scale ( $\approx 100$  GeV). Such an astonishing correction is perceived as very unnatural.

Numerous Beyond Standard Model theories (BSM) have been proposed in order to overcome the limits of the Standard Model.

Grand Unified Theories (GUT) aim at extending the symmetry group of the SM (eq. 1) into largest candidates, such as  $SU(10)$ ,  $SU(5)$  and  $E(6)$ . At GUT scale, approximately at  $10^{16}$  GeV, non-gravitational interactions are expected to be ruled by only one coupling constant,  $\alpha_{GUT}$ .

Super Symmetry (SUSY) models state that every fermion (boson) of the Standard Model has a bosonic (fermionic) superpartner, with exactly the same quantum numbers, except the spin. If SUSY is not broken, each couple of partners and superpartners should have the same masses, hypothesis easily excluded by the non-observation of the selectron. Super Symmetry represents a very elegant solution of the hierarchy problem of the Higgs boson mass, since the perturbative corrections brought by new SUSY particles exactly cancel out the divergences caused by SM particles corrections. A particular sub-class of SUSY models, Minimal Super Symmetric Standard Models, is characterized by the introduction of a new symmetry, the R-parity, that guarantees the proton stability and also the stability of the lightest SUSY particle, a possible good candidate for dark matter.

Two other possible theoretical pictures are extensively described in sec. 2.2-2.3.

## 2.2 Heavy Vector Triplet

The heavy vector triplet model [8] provides a general framework aimed at studying new physics beyond the standard model, that can manifest into the appearance of new resonances. The adopted approach is that of the simplified model, in which an effective Lagrangian is introduced, in order to describe the properties and interactions of new particles (in this case, a triplet of spin-1 bosons) by using a limited set of parameters, that can be easily linked to the physical observables at the LHC experiments. These parameters can describe many physical motivated theories (such as sequential extensions of the SM [9]- [10] or Composite Higgs [11]- [12]).

Since a simplified model is not a complete theory, its validity is restricted to the on-shell quantities related to the production and decay mechanisms of new resonances, that is the case of most of the LHC BSM searches are performed. Given these conditions, experimental results in the resonant region are sensitive to a limited number of the phenomenological Lagrangian parameters (or to a combination of those), whilst the remaining parameters tend to influence the tail of the distributions.

Limits on production cross-section times branching ratio ( $\sigma\mathcal{B}$ ), as a function of the invariant mass spectrum of the probed resonance, can be extracted from experimental data. Given that  $\sigma\mathcal{B}$  are functions of the simplified model parameters and of the parton luminosities, it is then possible to interpret the observed limits in the parameter space.

### 2.2.1 Simplified Lagrangian

The heavy vector triplet framework assumes the existence of an additional vector triplet,  $V_\mu^a$ ,  $a = 1, 2, 3$ , in which two spin-1 particles are charged and one is neutral:

$$V_\mu^\pm = \frac{V_\mu^1 \mp iV_\mu^2}{\sqrt{2}}; \quad V_\mu^0 = V_\mu^3. \quad (2.2)$$

The triplet interactions are described by a simplified Lagrangian, that is invariant under SM gauge and CP symmetry, and accidentally invariant under the custodial symmetry  $SU(2)_L \times SU(2)_R$ :

$$\begin{aligned} \mathcal{L}_V = & -\frac{1}{4} \left( D_\mu V_\nu^a - D_\nu V_\mu^a \right) \left( D^\mu V^{\nu a} - D^\nu V^{\mu a} \right) + \frac{m_V^2}{2} V_\mu^a V^{\mu a} \\ & + ig_V c_H V_\mu^a \left( H^\dagger \tau^a D^\mu H - D^\mu H^\dagger \tau^a H \right) + \frac{g^2}{g_V} c_F V_\mu^a \sum_f \bar{f}_L \gamma^\mu \tau^a f_L \\ & + \frac{g_V}{2} c_{VVV} \epsilon_{abc} V_\mu^a V_\nu^b \left( D^\mu V^{\nu c} - D^\nu V^{\mu c} \right) + g_V^2 c_{VVHH} V_\mu^a V^{\mu a} H^\dagger H - \frac{g}{2} c_{VW} \epsilon_{abc} W^{\mu\nu a} V_\mu^b V_\nu^c. \end{aligned} \quad (2.3)$$

In the first line of the formula 2.3,  $V$  mass and kinematic terms are included, described with the covariant derivative  $D_\mu V_\nu^a = \partial_\mu V_\nu^a + g\epsilon^{abc} W_\mu^b V_\nu^c$ , where  $W_\mu^a$  are the fields of the weak interaction and  $g$  is the weak gauge coupling.  $V_\mu^a$  are not mass eigenstates, since they mix with the electroweak fields after the spontaneous symmetry breaking, therefore  $m_V$  isn't the physical mass of the  $V$  bosons.

## 2.2 Heavy Vector Triplet

The second line describes the interaction of the triplet with the Higgs field and the SM left-handed fermions;  $c_H$  describes the vertices with the physical Higgs and the three unphysical Goldstone bosons that, for the Goldstone equivalence theorem, are connected to the longitudinal polarization of W and Z bosons at high-energy; hence,  $c_H$  is related to the bosonic decays of the resonances.  $c_F$  is the analogous parameter describing the  $V$  interaction with fermions, that can be generalized as a flavour dependent coefficient, once defined  $J_F^{\mu a} = \sum_f \bar{f}_L \gamma^\mu \tau^a f_L$ :  $c_F V_\mu^a J_F^{\mu a} = c_\ell V_\mu^a J_\ell^{\mu a} + c_q V_\mu^a J_q^{\mu a} + c_3 V_\mu^a J_3^{\mu a}$ .

### CHE COSA C'ENTRA IL GOLDSTONE BOSON EQUIVALENCE THEOREM CON LE W-Z AD ALTA ENERGIA? APPROFONDISCI

The last part of the equation does not describe vertices of  $V$  with SM fields, hence it can be neglected while describing the LHC phenomenology, under the assumptions previously made (**NEXT SECTION...**), along with dimension four quadrilinear  $V$  interactions, otherwise their effects would be appreciated in electroweak precision tests and precise Higgs coupling measurements [13].

The parameters in the Lagrangian can be interpreted as follows:  $g_V$  describes the strenght of the interaction, that is weighted by  $c$  parameters.  $g_V$  ranges from  $g_V \sim 1$  when the coupling is weak (sec. 2.2.4), to  $g_V \sim 4\pi$  when the coupling is strong (sec. 2.2.5).  $c$  parameters are expected to be  $c \sim 1$ , except to  $c_H$ , that can be smaller for weak couplings. The combinations describing the vertices,  $g_V c_H$  and  $g^2/g_V c_F$ , can be considered as the fundamental parameters, used to interpret the experimental results.

### 2.2.2 Mass eigenstates, mixing parameters and decay widths

The newly introduced  $SU(2)_L$  triplet is expected to mix with the weak SM fields. The  $U(1)_{em}$  symmetry is left unbroken by the new interaction, hence the massless combination of the electroweak fields, namely the photon, is the same as the SM:

$$A_\mu = B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W, \quad (2.4)$$

with the usual definitions of the electroweak parameters:

$$\begin{aligned} \tan \theta_W &= \frac{g'}{g} \\ e &= \frac{gg'}{\sqrt{g^2 + g'^2}} \\ g &= e / \sin \theta_w; g' = e / \cos \theta_w. \end{aligned} \quad (2.5)$$

The Z boson, on the other hand, mixes with the neutral component of the triplet,  $V^0$ , with a rotation parametrized with the angle  $\theta_N$ :

$$\begin{pmatrix} \cos \theta_N & \sin \theta_N \\ -\sin \theta_N & \cos \theta_N \end{pmatrix} \begin{pmatrix} Z \\ V^0 \end{pmatrix}. \quad (2.6)$$

The mass matrix of the rotated system is given by:

$$\mathbb{M}_N^2 = \begin{pmatrix} \hat{m}_Z^2 & c_H \zeta \hat{m}_Z \hat{m}_V \\ c_H \zeta \hat{m}_Z \hat{m}_V & \hat{m}_V^2 \end{pmatrix}, \quad (2.7)$$

where the parameters are defined as:

$$\begin{cases} \hat{m}_Z = \frac{e}{2 \sin \theta_W \cos \theta_W} \hat{v} \\ \hat{m}_V^2 = m_V^2 + g_V^2 c_{VHH} \hat{v}^2 \\ \zeta = \frac{g_V \hat{v}}{2 \hat{m}_V} \\ \frac{\hat{v}^2}{2} = \langle H^\dagger H \rangle \end{cases}, \quad (2.8)$$

and  $\hat{v}$ , the vacuum expectation value of the Higgs field, can be different from the SM  $v = 246$  GeV. The physical masses of  $Z$  and  $V^0$ ,  $m_Z$  and  $M_0$ , and  $\theta_N$  come from the matrix relations:

$$\begin{aligned} \text{Tr}(\mathbb{M}_N^2) &= \hat{m}_Z^2 + \hat{m}_V^2 = m_Z^2 + M_0^2 \\ \|\mathbb{M}_N^2\| &= \hat{m}_Z^2 + \hat{m}_V^2 (1 - c_H^2 \zeta^2) = m_Z^2 M_0^2 \\ \tan 2\theta_N &= \frac{2c_H \zeta \hat{m}_Z \hat{m}_V}{\hat{m}_V^2 - \hat{m}_Z^2}. \end{aligned} \quad (2.9)$$

The  $W^\pm$  bosons mix with the charged components of the triplet,  $V^\pm$ , leading to a mass matrix analogous to eq. 2.10:

$$\mathbb{M}_C^2 = \begin{pmatrix} \hat{m}_W^2 & c_H \zeta \hat{m}_W \hat{m}_V \\ c_H \zeta \hat{m}_W \hat{m}_V & \hat{m}_V^2 \end{pmatrix}, \quad (2.10)$$

where  $\hat{m}_W$  is defined as:

$$\left\{ \begin{array}{l} \hat{m}_W = \frac{e}{2 \sin \theta_W} \hat{v} = \hat{m}_Z \cos \theta_W \end{array} \right.; \quad (2.11)$$

the physical masses of  $W$  and  $V^\pm$ ,  $m_W$  and  $M_\pm$ , and the angle  $\theta_C$  parametrizing the rotation of the charged sector are described by:

$$\begin{aligned} \text{Tr}(\mathbb{M}_C^2) &= \hat{m}_W^2 + \hat{m}_V^2 = m_W^2 + M_\pm^2 \\ \|\mathbb{M}_C^2\| &= \hat{m}_W^2 + \hat{m}_V^2 (1 - c_H^2 \zeta^2) = m_W^2 M_\pm^2 \\ \tan 2\theta_C &= \frac{2c_H \zeta \hat{m}_W \hat{m}_V}{\hat{m}_V^2 - \hat{m}_W^2}. \end{aligned} \quad (2.12)$$

The custodial symmetry of eq. 2.3 guarantees that:

$$\mathbb{M}_C^2 = \begin{pmatrix} \cos \theta_W & 0 \\ 0 & 1 \end{pmatrix} \mathbb{M}_N^2 \begin{pmatrix} \cos \theta_W & 0 \\ 0 & 1 \end{pmatrix}. \quad (2.13)$$

By taking the determinant of this matrices, a custodial relation among the masses can be extracted:

$$m_W^2 M_\pm^2 = \cos \theta_W m_Z^2 M_0^2, \quad (2.14)$$

that has some very important consequences.

Given that this model aims at searching new particles in the TeV scale and that the scale of the electroweak interactions must lay at  $\sim 100$  GeV, a hierarchy of the physical masses seems very natural:

$$\frac{\hat{m}_{(W,Z)}}{\hat{m}_V} \sim \frac{m_{(W,Z)}}{M_{(\pm,0)}} \ll 1; \quad (2.15)$$

## 2.3 Warped extra dimension

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$\zeta$  parameter can be  $\zeta \ll 1$  (weakly coupled scenario) or  $\zeta \sim 1$  (strongly coupled scenario). When eq. ?? applies, the second lines in eq. 2.9 and eq. 2.12 can be approximated as follows:

$$\begin{aligned} m_Z^2 &= \hat{m}_Z^2 (1 - c_H^2 \zeta^2) (1 + \mathcal{O}(\hat{m}_Z^2 / \hat{m}_V^2)) \\ m_W^2 &= \hat{m}_W^2 (1 - c_H^2 \zeta^2) (1 + \mathcal{O}(\hat{m}_W^2 / \hat{m}_V^2)) \end{aligned} \quad (2.16)$$

From eq. 2.11, the ratio of the physical masses of the charged and neutral electroweak bosons can be approximated as:

$$\frac{m_W^2}{m_Z^2} \approx \cos^2 \theta_W, \quad (2.17)$$

that satisfies the SM tree-level relation  $\rho = 1$  if  $\cos^2 \theta_W \approx 1 - 0.23$ . Adding this approximation into eq. 2.14, the  $V$  bosons are expected to have the same masses, hence the same production rates:

$$M_\pm^2 = M_0^2 (1 + \mathcal{O}(\%)). \quad (2.18)$$

Another consequence of the mass hierarchy (2.15) is that the mixing angles  $\theta_{(N,C)}$  between the electroweak fields and the triplet are small:

$$\theta_{(N,C)} \approx c_H \zeta \frac{\hat{m}_{(W,Z)}}{\hat{m}_V} \ll 1, \quad (2.19)$$

hence the couplings among SM particles are very close to the SM couplings.

### 2.2.3 HVT productions

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### 2.2.4 Model A: weak coupling scenario

### 2.2.5 Model B: strong coupling scenario

## 2.3 Warped extra dimension





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<sup>177</sup> *Chapter 3*

<sup>178</sup> *Data and Monte Carlo samples*



179 *Chapter 4*

180 *Physics objects*



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<sup>181</sup> *Chapter 5*

<sup>182</sup> *Diboson candidate reconstruction*



183 *Chapter 6*

184 *Background estimation*





185 *Chapter 7*

186 *Systematic uncertainties*



187 *Chapter 8*

188 *Results*



189 *Chapter 9*

190 *Conclusions*



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