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SEARCH FOR SIGNATURES OF A NEW NEUTRAL SCALAR IN THE W^+W^- CHANNEL WITH SEMI-LEPTONIC FINAL STATES AT THE LHC

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Abstract

The Standard Model is the theoretical scheme currently adopted for the description of the fundamental interactions. Nevertheless, the desire to achieve a more complete formulation of nature, in which the Standard Model can be embedded, is driven by the presence of observational evidence that is unexplainable within the Standard Model description. Our purpose is to illustrate a method to conduct a phenomenological investigation regarding the existence of an enlarged Higgs sector. The beyond Standard Model contributions that will be considered arise from the presence of an extra scalar, CP-even and heavier with respect to the particle that has been discovered in 2012. The theoretical scheme in which the analysis will be embedded is the Singlet Extension, and the decay channel that will be taken into account will be the W^+W^- with semi-leptonic final states. The possibility of having visible signatures at the LHC will be discussed.

1 Introduction

The Standard Model (SM) has been experimentally proved to be the most successful framework to describe in a unified way the electromagnetic and weak interactions. An important ingredient of such model is the Brout–Englert–Higgs (BEH) mass generation mechanism [1, 2), which predicts the presence of a fundamental massive spin-zero particle in the theory spectrum whose characteristics are compatible with the particle discovered on 2012 by the CMS and ATLAS collaborations at the Large Hadron Collider (LHC) [3, 4). Nevertheless, the currently available measurements for such particle's interactions, both with the SM matter and with itself, are not sufficiently precise to fully validate the SM BEH prediction. This experimental status, along with the presence of physics phenomena that cannot be described in the SM, leave open access to Beyond Standard Model (BSM) theories. Among the physically motivated BSM frameworks that have been proposed, some of them include an enlargement of the Higgs sector.

In the context of New Physics (NP) investigations, phenomenological analyses are of primary importance as they operate as intermediary between the theoretical framework and the experimental measurements by studying how the BSM signals would appear in the detectors. For theories where the new physics contributions arise at the electroweak scale or higher ones, the environment where experimental tests are mainly carried out are the colliders. To perform accurate phenomenological analyses, the high energy physics community relies on the employment of events generators, such as MadGraph5_aMC@NLO 5, 6), that provide the access to the kinematic information of the initial particles and the final products.

The purpose of this phenomenological study is to present a method for the investigation regarding the possible signatures coming from an enlarged Higgs sector that can manifest themselves at the LHC. The NP contribution considered is due to the presence of an extra scalar S, heavier with respect to the 125 GeV particle. The channel exploited for the analysis is the W^+W^- channel with semi-leptonic final states. This scenario was selected because the CMS collaboration observed an upward fluctuation of data compared with the expected background in the search for a high mass Higgs-like scalar boson decaying into a pair of W bosons with fully-leptonic final states 7). This excess has to be confirmed by the new analyses, including those in the same channel with semi-leptonic final states here taken into account.

2 Lagrangian for the enlarged Higgs sector

To consider general models that extend the SM description including the presence of at least one extra scalar in the Higgs sector, the SM Lagrangian must be modified. In particular, we have considered the modifications as additive to the SM, and separated them in two different contributions, as described by the following equations.

$$\mathcal{L}_{BSM} = \mathcal{L}_{SM} + \mathcal{L}_S + \mathcal{L}_{hMOD} \tag{1}$$

$$\begin{aligned}\mathcal{L}_S \;=\; & \frac{1}{2}\partial_\mu S \partial^\mu S \;-\; \frac{1}{2}M_S^2 S^2 \;+\; \frac{2m_W^2}{v}(k_{sww}) S W_\mu^+ W_-^\mu \;+\; \frac{m_W^2}{v\; cos^2\theta_w}(k_{szz}) S Z_\mu Z^\mu + \\ & +\; k_{stt}\; S\bar{t}t \;+\; k_{sbb}\; S\bar{b}b \;+ k_{s\tau\tau}\; S\bar{\tau}\tau \;+ ...\end{aligned} \tag{2}$$

$$\mathcal{L}_{hMOD} = \frac{2m_W^2}{v}(k_{hww}) h W_\mu^+ W_-^\mu \;+\; \frac{m_W^2}{v\; cos\theta_w^2}(k_{hzz}) h Z_\mu Z^\mu - \frac{k_{htt}}{\sqrt{2}}\; h\bar{t}t - \frac{k_{hbb}}{\sqrt{2}}\; h\bar{b}b + ... \tag{3}$$

The term $\mathcal{L}_S$ describes the dynamic and the interactions for the new scalar S, which is a colourless and electromagnetically neutral particle with mass M_S. In equation 2 are reported the terms that allow to describe the two production mechanisms for the extra scalar that are assumed to be the dominant ones, *i.e.* the Gluon Gluon Fusion (GGF) and Vector Boson Fusion (VBF), as well as all the possible leading order two-body decays. Different normalizations for the various couplings have been assumed, for example the vertices involving two massive gauge bosons have been normalized to the SM value for the Higgs' interaction.

The following term, $\mathcal{L}_{hMOD}$, is necessary to describe scenarios where the couplings for the Higgs particle (h) are different with respect to the SM predictions, as occurs when there is a mixing between the interaction eigenstates in the scalar sector. The BSM parameters entering the Lagrangian $\mathcal{L}_{BSM}$, namely the mass for the extra scalar and all the couplings for the vertices in equations 2-3, have been defined to be free and independent. This choice was performed to allow the usage of the aforementioned Lagrangian to describe various BSM scenarios with at least one extra scalar, each of which with a different internal dependence among the free parameters that must be properly stated before the analysis. This procedure will be adopted in section 4, performing the analysis for the Singlet Extension.

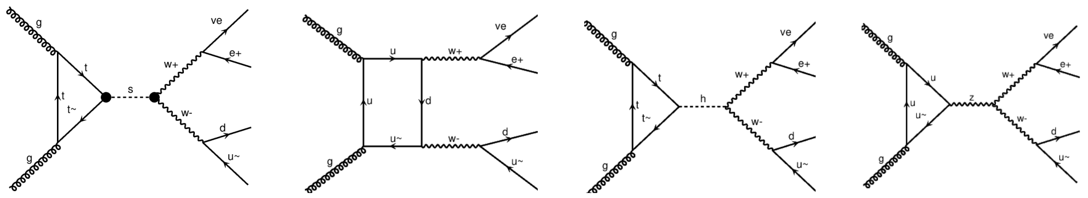
The structure of the BSM Lagrangian in equations 1-3 was implemented [1] also in the input file for the event generator, encoded in the *Universal FeynRules Output* (UFO) format 8). Moreover, a peculiar labelling for the BSM interaction vertices allowed us to exploit the Lagrangian to obtain a set of simulated events separately for the signal and the background contributions, as well as to deconstruct the interference contributions between the signal and the SM background, as shown in the following section.

3 SM-like high mass scalar resonance

As illustrative example, we consider a scenario where the two scalars S, h have both SM-like couplings, *i.e.* whose strength is fixed to the value predicted for the SM Higgs. Therefore, the only NP source is represented by the presence of the S particle. It is important to underline that this scenario represents a preliminary test for the analysis procedure that can be used for general BSM frameworks.

Fixing the mass of the extra scalar S to $M_S = 600\text{GeV}$, we checked that the dominant production mechanism is the GGF, so that, in first approximation, we can consider only this one. Therefore, we analysed the behaviour of the signal events, represented by those that have been mediated by an exchange of the S particle in the s-channel, produced via a virtual loop of quarks, and that decays in a couple of W bosons.

Keeping the same initial and final states, *i.e.* two incoming gluons (g) and semi-leptonic final states ($l\nu qq'$) resulting from the decay of a couple of W bosons respectively, our setup allows us to take into account the interference of the signal diagrams with the SM loop-induced source of background in the W^+W^- channel (*Interference s-B*). This contribution can be separated in the interference between signal diagrams and those involving a SM Higgs h exchange (*Interference s-h*) and in the interference between signal diagrams and the loop-induced SM background in the W^+W^- channel without the contributions involving a SM Higgs h exchange (*Interference s-b*). Some of the diagrams involved in the signal and interference contributions for the scattering processes of interest are shown in figure 1.



(a) (b) (c) (d)

Figure 1: *Example of a signal diagram* (a), *where the NP vertices are marked with a black dot, and some SM background diagrams at loop-level in the W^+W^- channel* (b)-(d).

In figure 2 the signal and interference contributions to the cross section $\sigma(gg \to W^+W^- \to l\nu qq')$ are shown. Here we plot the invariant mass distributions for the four parton-level final products. The simulations were performed mimicking LHC collisions occurring at a $\sqrt{s} = 13$ TeV center of mass energy and the integrated luminosity assumed was 35.9 fb^{-1}: those characteristics are intended to recreate the set of data collected by the CMS collaboration at the LHC during Run-2 in 2016. Moreover, for the W decaying leptonically, we considered only the products coming from the first and second generation.

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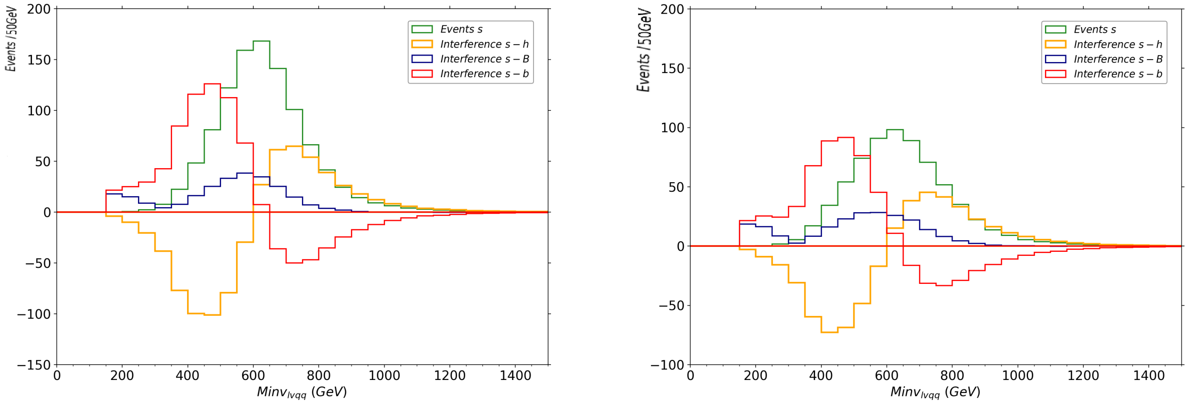
[1] by L. Panizzi (private communication).

The results are obtained assuming two different widths for the extra scalar $\Gamma_S = 300, 400$ GeV. The scenario where the width exceeds the value predicted for SM-like couplings and a mass of $M_S = 600$GeV takes in account, for example, the presence of other BSM particles as possible decay products for S, that will increase its decay probability and, consequently, its width. We see that the two decomposed interference contributions s-h, s-b have a similar behaviour with an opposite sign, switching respectively from destructive to constructive and vice versa. This evolution occurs in correspondence of the scalar S pole mass value. Their combined result is summed to a total constructive contribution s-B.



(a) $\Gamma_S = 300$ GeV

(b) $\Gamma_S = 400$ GeV

Figure 2: *GGF parton-level invariant mass distributions for signal events (s) and the various interference contributions: with the SM Higgs in the* W^+W^- *channel (s-h, yellow), with the SM one-loop background in the* W^+W^- *channel (s-B, blue) and with SM one-loop background in the* W^+W^- *channel without the h contributions (s-b, red). Here* M_S*=600 GeV and* Γ_S*=300,400 GeV.*

The capability of this deconstructing mechanism, here briefly illustrated, will be fruitful in scenarios where there are different signal contributions. In fact, it will allow to study both the interference between the various source of signal as well as with the SM background.

4 Test of the Singlet Extension

One of the most simple BSM frameworks describing an extra scalar whose parameter space is still partially available is undoubtedly the Singlet Extension (SE) [10, 11].

In this model a new scalar σ, singlet under the gauge interactions, is added to the Lagrangian. It interacts exclusively with the SM Higgs doublet (Φ) through a scalar potential $V(\Phi, \sigma)$. Assuming the presence of an additional $\mathbb{Z}_2$ symmetry which is spontaneously broken by the singlet, the Lagrangian for the Higgs sector is:

$$\mathcal{L}_{Higgs} = (D^\mu\Phi)^\dagger(D_\mu\Phi) + \partial^\mu\sigma\partial_\mu\sigma - V(\Phi, \sigma), \tag{4}$$

$$V(\Phi, \sigma) = -m^2\Phi^\dagger\Phi - \mu^2\sigma^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2\sigma^4 + \lambda_3\Phi^\dagger\Phi\sigma^2. \tag{5}$$

In the scenario were both the doublet and the singlet acquire a non-zero Vacuum Expectation Value (VEV), defined as $v \sim 246$GeV for the doublet and a free-valued v_s for the singlet, their expression in the unitary gauge is:

$$\Phi = \begin{pmatrix} 0 \\ \frac{\phi_0+v}{\sqrt{2}} \end{pmatrix} \qquad\qquad \sigma = \frac{\phi_s + v_s}{\sqrt{2}}. \tag{6}$$

The diagonalization of the squared mass matrix arising from the potential in equation 5 allows the identification of the mass eigenstates ($h,\ S$) that are obtainable from the gauge eigenstates (ϕ_0, ϕ_s) through a rotation matrix defined by the mixing angle α, satisfying the relation:

$$\phi_0 = \cos\alpha\ h + \sin\alpha\ S. \tag{7}$$

The hierarchy between the physical masses is $m_h^2 \leq M_S^2$, and the the picture where h represents the discovered LHC particle, which we will adopt for the following discussion, corresponds to the *small mixing angle scenario* ($\sin\alpha \to 0$). From equation 7 it is also possible to describe the interactions with the SM particles that the two mass eigenstates will inherit from the gauge eigenstate ϕ_0: the strength for each coupling involving one $h(S)$ field will be suppressed with respect to the SM value by a factor $\cos\alpha(\sin\alpha)$. Therefore, the majority of the BSM coupling won't be all independent, being a combined function of the SM value and the mixing angle.

This framework can be tested with our previously described method. Fixing the values for m_h and v, the SE free parameters are only three 11): the mixing angle α, the ratio between the VEVs $\tan\beta = v/v_s$ and the mass of the heavy scalar M_S. To consider a BSM theory as a viable candidate to describe the fundamental interactions some theoretical and experimental bounds must be satisfied, and this constrains the possible values for the free parameters of the theory. For the SE, the bounds that must be satisfied are:

- Perturbativity of the couplings entering the scalar potential, tree-level perturbative unitarity for 2→2 scattering processes and condition for the scalar potential to be bounded from below 11);
- Compatibility of the loop corrections to the gauge bosons' vacuum polarization with the current measured values for the electroweak precision observables (EWPO).
- Compatibility of the SE signal predictions with the exclusion limits resulting from additional scalar searches carried out at colliders and with the measurements of the 125 GeV Higgs properties. Those can be tested using the public code `HiggsTools` 15).

The resulting parameter space is quite constrained, in particular only small values for $\sin\alpha$ are allowed. This is justified by the current measured precision for the interaction strengths of the LHC Higgs with a couple of massive vector bosons. For the SE those measurements constraint $\cos\alpha$ according to equation 7 and, consequently, the value of $\sin\alpha$.

For example, some allowed values are $\sin\alpha = 0.1$, $\tan\beta = 0.1$ and four different mass hypotheses $M_S = 200, 650, 1000, 1500$ GeV. For those scenarios, the expected distributions for the NP signal can be studied, defining it to be generated by all the diagrams mediated by an s-channel exchange of the S particle produced via GGF [2]. To investigate the presence of visible signatures of those processes, we can compare the number of signal events expected for each invariant mass value with the number of events expected for the SM background. In the following discussion the results will be presented for a parton-level analysis, with the invariant mass defined by the kinematics of the four semi-leptonic final

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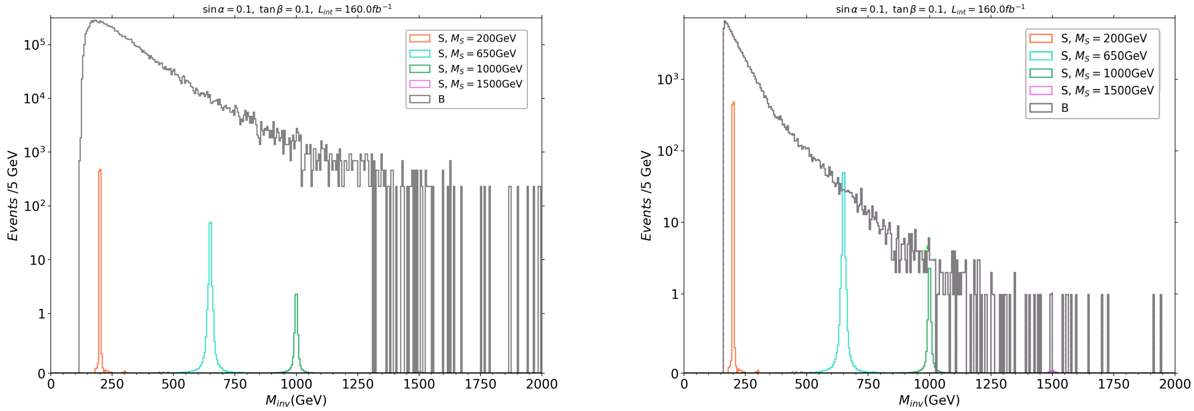
[2] The GGF is the dominant production mechanism at least for $M_S = 200, 650$ GeV.

products, as shown in figure 3. The plots have been obtained simulating the Run-2 LHC configuration, assuming a center of mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of $\mathrm{L}_{int} = 160\ \mathrm{fb}^{-1}$. The width Γ_S was evaluated summing all the contributions of the accessible two-body decays.



(a) *Background SM tree-level*

(b) *Background SM loop-induced (W^+W^- channel)*

Figure 3: *Number of events expected for signal (S) and SM background (B) for* $\sin\alpha = 0.1$, $\tan\beta = 0.1$ *and various mass hypotheses, for two sources of SM background.*

The main source of background assuming the same initial (gg) and final states ($l\nu qq'$) is the one that originates from the tree-level contribution ((a) in figure 3), and that has a cross section that is at least four order of magnitude higher with respect to the signal ones. We can see that in absence of specific cuts that are able to lower partially those background contributions - such as requiring that the invariant mass of the two jets lies around the W mass - the possibility to have an evidence of the signal contributions is absent.

Another source of background, that is obtainable with a different simulation, is the loop induced one in the W^+W^- channel, ((b) in figure 3, presented in scale with signal events). This contribution will be fundamental for the analysis only if the cuts on the tree-level source will be able to lower its number of expected events of at least two order of magnitude. With the current setup, the possibility to prove the Singlet Extension in the W^+W^- channel with semi-leptonic final states appears to be a challenging task for the signal hypotheses here tested, also after the High Luminosity phase of the LHC.

5 Conclusions

We have described a general approach to perform phenomenological studies of BSM signatures arising at the LHC in the W^+W^- channel with semi-leptonic final states due to the presence of an enlarged Higgs sector comprising one extra scalar that can be produced via GGF and VBF. We illustrated two scenarios for the study of the signal, interference and background events: the analysis of general models, where the two scalars in the Higgs sector have SM-like couplings, and the analysis of some viable configurations for the Singlet Extension scheme. Both the analyses were based on parton-level results and on the assumption of GGF production mechanism for the new particle. For the first scenario, we illustrated how it is possible to deconstruct the interference contributions between the signal and the SM background in order to separately study their impact. For the second analysis, we discussed the possibility of identifying some BSM signatures in the differential distribution of the invariant mass of the decay products. This appears to be a challenging task. Nevertheless, to understand definitely whether it is possible to test the SE framework with this methodology, some additional analyses must be performed, taking into account the interference contributions, the VBF production scenario for the extra scalar and the impact of the cuts on the SM background.

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