Unitarity-controlled resonances after the Higgs boson discovery

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If the recently discovered Higgs boson's couplings deviate from the Standard Model expectation, we may anticipate new resonant physics in the weak boson fusion channels resulting from high scale unitarity sum rules of longitudinal gauge boson scattering. Motivated by excesses in analyses of multi-leptons + missing energy + jets final states during run 1, we perform a phenomenological investigation of these channels at the LHC bounded by current Higgs coupling constraints. Such an approach constrains the prospects to observe such new physics at the LHC as a function of very few and generic parameters and allows the investigation of the strong requirement of probability conservation in the electroweak sector to high energies.

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I. INTRODUCTION

After the discovery of the Higgs boson [1] at the LHC and first preliminary tests of its coupling structure and strengths [2,3], a coarse-grained picture of consistency with the Standard Model (SM) has emerged. Resulting from Higgs quantum numbers, current constraints on the Higgs boson's couplings, assuming a SM value of the Higgs width or an upper limit on the Higgs coupling to electroweak gauge bosons, indicate that the Higgs couplings to electroweak bosons agree with the SM expectation within $\mathcal{O}(10\%)$ [4,5]. This establishes the Higgs's involvement in electroweak symmetry breaking and its role in the unitarization of massive longitudinal gauge boson scattering.

However, current constraints leave a lot of space for deviations from the SM-like implementation of electroweak symmetry breaking. In particular, small deviations from the SM Higgs coupling pattern are expected in a very broad class of models that explain the presence of the electroweak scale as a dimensional transmutation effect [6,7]. In particular, these include composite Higgs scenarios where we expect new contributions from composite states analogous to the rho meson [8]. Explicit examples have been discussed in the literature, mostly in the context of AdS/CFT duality, see e.g. [9].

Owing to the fact that any modification from the SM Higgs couplings explicitly introduces unitarity violation, novel resonant physics is likely to enter at a scale $Q^2 \gg m_h^2$ to conserve probability [10] if we indeed deal with non-SM Higgs interactions. Weak boson scattering processes are theoretically well motivated probes of such a dynamics, correlating the size of the new physics effects with the deviation of the observed Higgs phenomenology from the SM.

Accessing longitudinal gauge boson scattering [which is highly sensitive to beyond the Standard Model (BSM) effects] at the LHC in a phenomenologically useful way is difficult. Due to almost conserved light quark and lepton currents, weak boson fusion (WBF, for analyses see [11,12]) is not too sensitive to modifications of the involved Higgs couplings.[1] The Higgs exchange at energies $m(VV) \gg m_h$ in a Higgs doublet model provides a destructive contribution to $VVqq(V = W^\pm, Z)$ production. Thus, a ∼10% cross section excess at the LHC for inclusive WBF is mainly due to the smaller destructive Higgs contribution for smaller couplings, rather than diverging $qq \to qqVV$ processes getting tamed by the polynomial parton density function suppression at large parton energy fractions.

Nevertheless, it is important to realize that, if $V_L V_L \to V_L V_L$ (Fig. 1) scattering violates the unitarity bound, the (leading order) electroweak sector becomes ill defined, and there is no theoretically consistent interpretation of

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[1] In a general gauge the Goldstone contributions to the amplitude vanish in the chiral limit, signaling a vanishing contribution from longitudinal degrees of freedom at high invariant masses.

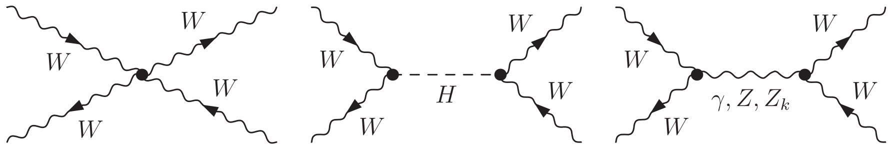

FIG. 1. Sample Feynman diagrams contributing to $WW \to WW$, the t-channel diagrams are not shown.

constraints and measurements even if the alternate hypothesis seems well behaved [13].

Current analyses mostly focus on studying the impact of a subset of the 59 dimension-six operators (neglecting flavor structures) [14] on Higgs physics in the on- and off-shell region. In this paper, we take a complementary approach and address the question of what to expect in WBF processes when unitarity is explicitly enforced by additional resonances in the TeV regime, following a strong-interaction paradigm.

If additional resonances in VV scattering are present, an identification will depend on their mass, width and coupling strengths, fixed through high scale unitarity as a function of their spin: The naive growth proportional to s^2 and s of the amplitude, depicted in Fig. 1, in the high energy limit $\epsilon_L^\mu(p) \sim p^\mu/m_V$ is mitigated by imposing sum rules that link quartic and trilinear gauge and Higgs couplings (see also [15–17] for a similar discussion of the pure Higgs-less case). The discovery of particles categorized as Eq. (1)(a)–(d) in the $VVjj$ channels would provide a conclusive hint for the role of new resonances in electroweak symmetry breaking. It is intriguing that both ATLAS and CMS have observed nonsignificant excesses in (multi-)lepton $+\not{E}_T+$ jets searches [18]; we take this observation as another motivation for an as model-independent as possible analysis of these final states.

For SM-like WW scattering, the sum rules read

$$g_{WWWW} = g^2_{WW\gamma} + \sum_i g^2_{WWZ_i} \tag{1a}$$

$$4m_W^2 g_{WWWW} = \sum_i 3m_i^2 g^2_{WWZ_i} + \sum_i g^2_{WWH_i}, \tag{1b}$$

and for $WW \to ZZ$ (and crossed) scattering these are modified to

$$g_{WWZZ} = \sum_i g^2_{W_iWZ} \tag{1c}$$

$$2(m_W^2 + m_Z^2) g_{WWZZ} = \sum_i \left(3m_i^2 - \frac{(m_Z^2 - m_W^2)^2}{m_i^2}\right) g^2_{W_iWZ} + \sum_i g_{WWH_i} g_{ZZH_i}. \tag{1d}$$

In these sums the index $i = 1$ refers to the SM W, Z and Higgs bosons, respectively, and $i > 1$ refer to a series of isotriplet massive vector bosons W', Z' and isosinglet H' scalar bosons, respectively.[2] Although we will not make contact with a concrete model, one can think of the $i > 1$ states as Kaluza-Klein states that arise in models with extra dimensions and dual interpretations thereof [9,16] as a guideline: $W_{i>1}$ can couple to SM W and Z bosons, while $Z_{i>1}$ can couple to a pair of SM W bosons etc. In concrete scenarios [8,9,16] the above sum rules are quickly saturated by the first $i \neq 1$ states. We assume that custodial $SU(2)$ is intact, which, in addition to the correct tree-level Z/W mass ratio, will leave imprints in the additional resonances spectrum, see e.g. [9]. The unitarity sum rules are independent of custodial isospin and since the sum rules are quickly saturated, custodial $SU(2)$ is not important for our investigation, but remains a testable concept in case of a discovery of additional vector resonances.

It is important to realize that due to $SU(2)_L$ invariance (e.g. the absence of a quartic Z interaction) the reasoning along the above lines does not apply to $ZZ \to ZZ$ scattering. In the high energy regime the Higgs exchange diagrams conspire:

$$\mathcal{M}(Z_L Z_L \to Z_L Z_L) \sim s + t + u = 4m_Z^2, \tag{2}$$

i.e. the scattering amplitude becomes independent of the center of mass energy. Hence, on the one hand, in scenarios where unitarity in WW and WZ scattering is enforced by isovectors, we do not expect new resonant structures in $pp \to 4\ell + 2j$. On the other hand if unitarity is conserved via the exchange of isoscalar states, this channel will provide a phenomenological smoking gun. Obviously this is not a novel insight and under discussion in the context of e.g. Higgs portal scenarios [20]. We will not investigate the ZZ channel along this line in further detail.

For the purpose of this paper we start with a minimal, yet powerful set of assumptions that can be reconciled in models that range from (perturbative and large N) AdS/CFT duality over supersymmetry to simple Higgs portal scenarios. We will focus on a vectorial realization of unitarity, assuming an electroweak doublet nature of the Higgs boson.[3] This represents an alternative benchmark of new resonant physics involved in the mechanism of electroweak symmetry breaking (EWSB) which has been largely ignored since the Higgs discovery so far.

[2]It is worth noting that similar sum rules cannot be formulated for isotensors [19].

[3]See [21] for a detailed discussion of WBF signatures in Higgs triplet scenarios.

The first rule of Eq. (1)(a) and (c) is typically a consequence of gauge invariance [16] while the second rule reflects the particular mechanism of EWSB. Similar sum rules exist for massive $q\bar{q} \to V_L V_L$ scattering, linking the Yukawa sector to the gauge sector [22]. We are predominantly interested in a modified Higgs phenomenology in the standard WBF search channels. It is however important to note that the latter sum rules also predict new resonant states in Drell-Yan-type production [23] (for a recent comprehensive discussion see also [24]) or gluon fusion induced $VVjj$ production. For this analysis, gluon fusion events can efficiently be removed by imposing selection criteria [25]; this process is neglected further on (see below).

The presence of unitarizing spin one resonances is tantamount to a modification of the 4-point gauge interactions when we choose the trilinear couplings to be SM-like. In higher dimensional and dual composite Higgs scenarios this fact is typically encoded in multiple definitions of the tree-level Weinberg angle and a resulting constraint from the ρ parameter. The quartic gauge couplings are currently not well constrained and we use this freedom to saturate the above sum rules via a nonstandard value of g_{WWWW} and g_{WWZZ}. The numerical modifications away from the SM values as a function of the modified Higgs couplings is small, $\simeq 0.1\%$, especially in the vicinity of the SM when $g_{WWZ'} = g_{W'WZ} = 0$ are small and well within the latest quartic coupling measurements' uncertainty as performed during the LEP era [26].[4]

II. RESULTS

A. Details of the simulation

Using Eq. (1)(a)–(d), we have a simple parametrization of new physics interactions in terms of the mass and width of the new vector state, and Higgs coupling modification parameter. Since we do not specify a complete model we treat the extra boson widths as nuisance parameters. In concrete models the width can span a range from rather narrow to extremely wide. Masses are typically constrained by electroweak precision measurements. Since the sum rules give an independent prediction, we will not consider these corrections further.

We use a modified version of VBFNLO [27] to simulate the weak boson fusion channel events for fully partonic final states inputting the relevant model parameters mentioned above. Since WBF can be identified as "double DIS (deep inelastic scattering)" we can efficiently include the impact of higher order QCD corrections on differential distributions by dynamically choosing the t-channel momentum transfer of the electroweak bosons as the factorization and renormalization scales [28] irrespective of new resonant structures in the leptonic final state [29]. We generate the gluon fusion contribution using again VBFNLO, but find that they are negligible for typical WBF requirements. As benchmarks we consider the following parameter points, defining $\alpha = g_H/g_H^{\mathrm{SM}}$,

$$\begin{aligned}
m_{W',Z'} &= 700\ \mathrm{GeV}, \qquad \Gamma_{W',Z'} = 3\ \mathrm{GeV}, \qquad \alpha = 0.9,\\
m_{W',Z'} &= 1000\ \mathrm{GeV}, \qquad \Gamma_{W',Z'} = 7\ \mathrm{GeV}, \qquad \alpha = 0.9,\\
m_{W',Z'} &= 700\ \mathrm{GeV}, \qquad \Gamma_{W',Z'} = 10\ \mathrm{GeV}, \qquad \alpha = 0.5,\\
m_{W',Z'} &= 1000\ \mathrm{GeV}, \qquad \Gamma_{W',Z'} = 30\ \mathrm{GeV}, \qquad \alpha = 0.5,
\end{aligned} \tag{3}$$

to highlight characteristics. Note that the values $\alpha > 1$ do not allow real coupling values in Eq. (1)(a)–(d) and we cannot incorporate this situation in model where the Higgs boson is an $SU(2)_L$ doublet. The chosen width values are small and neglect potentially large couplings to fermions, especially to the top quark. We use these values to establish an estimate on sensitivity for a particular resolution around the vector boson candidate's mass in Sec. II E. As we will see in Sec. II E, where we generalize away from the above assumptions, the signal quickly decouples.[5]

The VBFNLO event files are further processed with HERWIG++ [31] for showering and hadronization. For this study, we utilize leptonic final states exclusively at 14 TeV. As potential backgrounds we consider continuum WW, WZ and $t\bar{t}$ production and generate these events using ALPGEN [32].

Detector effects and reconstruction efficiencies are performed using a detector simulation based on the ATLAS Krakow parametrization [33]. The parameters employed provide conservative estimates of the ATLAS detector performance for the phase-II high-luminosity LHC. In particular we model pileup (at $\mu = 80$) and $\sum E_T$ dependent resolutions for jets and for p_T.

Jets are reconstructed with the anti-k_T jet clustering algorithm [34] with $p_T > 40$ GeV and resolution parameter $R = 0.4$. To parametrize jet resolutions, b-jet efficiencies and fake rates we follow [33] as well.

Charged leptons (electrons and muons) are considered to be isolated if $p_{T,l} > 10$ GeV and if the hadronic energy deposit within a cone of size $R = 0.3$ is smaller than 10% of the lepton candidate's transverse momentum in the rapidity range $|y_l| < 2.5$.

[4]On a theoretical level, a modification of the quartic interactions away from the SM expectation introduces issues with Ward identities which ultimately feed into the unitarity of the S matrix beyond the tree-level approximation. Hence, Eq. (1)(a)–(d) needs to be understood as an effective theory below the compositeness scale. In concrete scenarios motivated from AdS/CFT, the fundamental scale can be as high as 10 TeV [9,16] and the SM-like ward identities need to be replaced by the corresponding five-dimensional anti–de Sitter (AdS) relations.

[5]It is important to stress that new sources of theoretical uncertainties arise once the width becomes comparable to the resonance mass [30].

B. Projections for $2l + \not{E}_T + jj$ production

For the analysis of the $2l + \not{E}_T + jj$ channel, we follow the event reconstruction outlined in Sec. II A, and we require exactly two isolated leptons. We impose staggered cuts on the transverse momenta of both leptons, i.e.

$$p_{T,l_1} > 120\ \text{GeV},\quad p_{T,l_2} > 80\ \text{GeV}. \tag{4}$$

Additionally, for the two most forward jets with $p_T > 40$ GeV we impose a WBF selection of

$$y_{j_1} \times y_{j_2} < 0,\quad |y_{j_1} - y_{j_2}| > 4.0,\quad m_{j_1 j_2} > 800\ \text{GeV}. \tag{5}$$

The heavy resonance is reconstructed by requiring the transverse mass $m_T > 350$ GeV where

$$m_{T,2l}^2 = \left[\sqrt{m_{l_1 l_2}^2 + p_{T,ll}^2} + |p_{T,\text{miss}}|\right]^2 - [p_{T,ll} + p_{T,\text{miss}}]^2. \tag{6}$$

We show the results after each analysis step in Table I. The WW channel is the most complicated final state in terms of background composition and final state reconstruction given the expected detector performance.

There are two major conclusions at this stage:

(i) Due to the departure of $\alpha < 1$, a continuum enhancement for the BSM signal over the expected electroweak $VVjj$ distribution is present. This excess is not big enough to be useful to constrain this scenario efficiently; this also applies to the novel nonresonant t- and u-channel contributions. When we approach the SM limit (as supported by current measurements) the signal contributions quickly decouple and the analysis loses sensitivity even for small widths. In this sense, the phase space region complementary to the on-shell Higgs region cannot be efficiently exploited phenomenologically. Deviations from the SM WBF hypothesis are typically of the order of 10%, which can easily be obstructed by additional experimental and theoretical systematics (see e.g. [35]) neglected in this analysis. The gluon fusion contribution is highly suppressed and we do not include it in Fig. 3.

(ii) We therefore proceed to reconstruct the presence of s-channel resonances in a bump search sensitive to both the $WWjj$ and $ZZjj$ subprocesses. The $2l + \not{E}_T + jj$ final state, however, is also characterized by a relatively large fraction of missing energy, which substantially hampers a bump search, Fig. 3(a). This again becomes more severe when we turn to Higgs couplings in the vicinity of the SM expectation, see Fig. 2.

TABLE I. Results for 2 lepton search. The cross sections are given in femtobarn, corresponding to proton-proton collisions at $\sqrt{s} = 14$ TeV. Further details on the cuts can be found in the text.

Sample	Lepton cuts	WBF cuts	$m_{T,2l}$
$(h \to WW)jj$ GF	0.03	<0.01	<0.01
$t\bar{t}$ + jets	82.76	0.22	0.17
WW + jets	6.32	1.72	1.09
WZ + jets	0.47	0.07	0.04
ZZ + jets	0.64	0.12	0.06
Z + jets	0.08	<0.01	<0.01
$m_{W',Z'} = 700$ GeV, $\alpha = 0.9$	6.37	1.84	1.24
$m_{W',Z'} = 1000$ GeV, $\alpha = 0.9$	5.89	1.68	1.18
$m_{W',Z'} = 1500$ GeV, $\alpha = 0.9$	5.80	1.67	1.13
$m_{W',Z'} = 2000$ GeV, $\alpha = 0.9$	5.84	1.64	1.09
$m_{W',Z'} = 700$ GeV, $\alpha = 0.5$	8.43	2.30	1.73
$m_{W',Z'} = 1000$ GeV, $\alpha = 0.5$	6.85	1.96	1.41
$m_{W',Z'} = 1500$ GeV, $\alpha = 0.5$	6.44	1.78	1.22
$m_{W',Z'} = 2000$ GeV, $\alpha = 0.5$	6.36	1.77	1.17

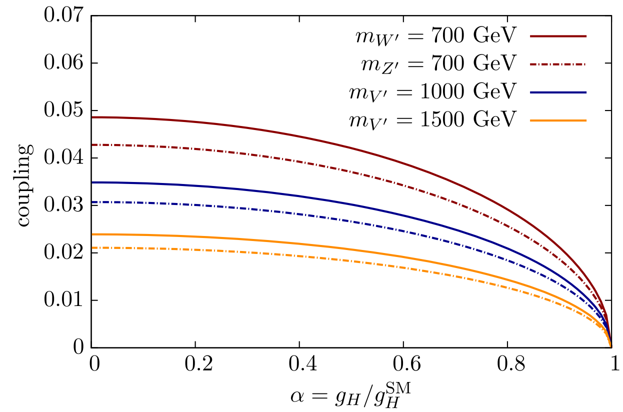

FIG. 2 (color online). W' and Z' couplings to SM W and Z bosons as a function of the Higgs coupling deviation following from Eq. (1)(a)–(d).

C. Projections for WBF $4l + jj$ production

The systematic shortcomings resulting from the missing transverse energy in the WW final state are not present in the fully reconstructible final state $4l + jj$. We require

TABLE II. Results for the four lepton search. The cross sections are given in femtobarn, corresponding to proton-proton collisions at $\sqrt{s} = 14$ TeV. The t- and u-channel mass scales have no significant impact. Further details on the cuts can be found in the text.

Sample	Lepton cuts	WBF cuts	m_{4l}
ZZ + jets	0.25	0.074	0.054
$\alpha = 0.9$	0.23	0.075	0.053
$\alpha = 0.5$	0.24	0.078	0.058

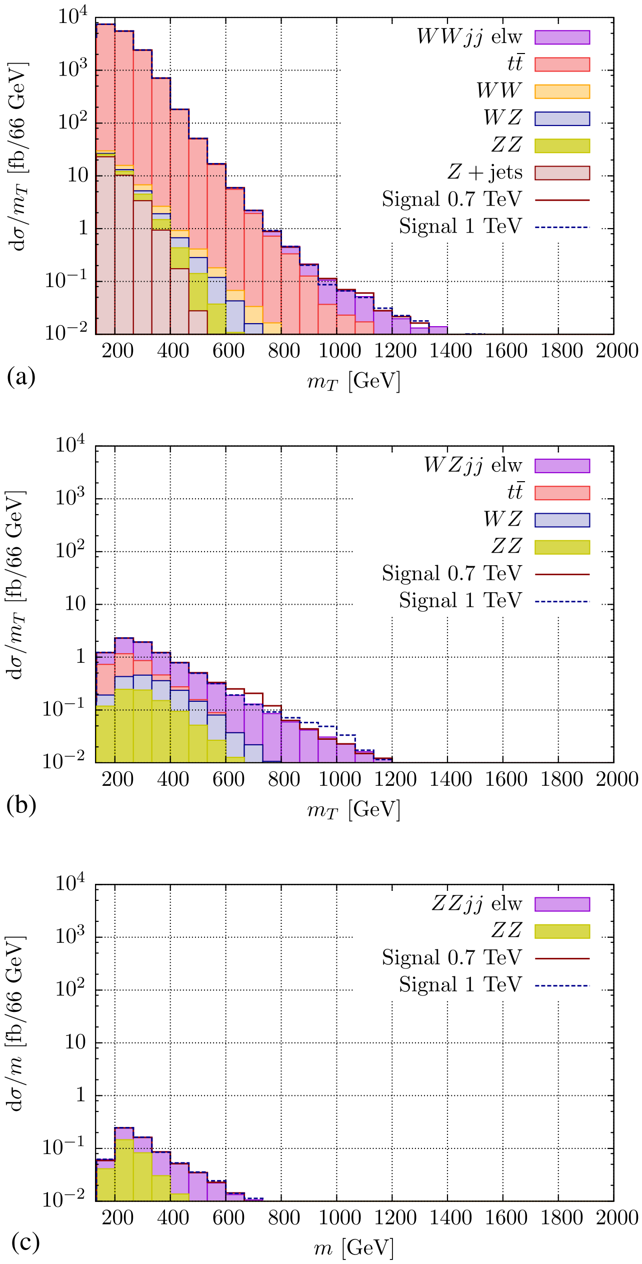

FIG. 3 (color online). Results of the WBF analysis in the $2\ell + \not{E}_T + jj$ channel (a), the $3\ell + \not{E}_T + jj$ channel (b) and the $4\ell + jj$ channel (c). All signals refer to a choice of $\alpha = 0.9$. Transverse mass distribution of the (a) $2\ell + \not{E}_T + jj$; (b) $3\ell + \not{E}_T + jj$; (c) $4\ell + jj$ final state after requesting exactly two isolated leptons, as outlined in Sec. II B.

exactly four leptons and follow Eqs. (4) and (5). Additionally, the four lepton mass is required to be $m_{4l} > 350$ GeV. The cut flow is depicted in Table II. The backgrounds are manageable, however, for the considered scenario there is no s-channel resonance and again the continuum enhancement is too small to provide solid discrimination from a non-SM realization of EWSB, if we compare the deviations of Table II to $\mathcal{O}(10\%)$ expected

TABLE III. Results for the three lepton search. The cross sections are given in femtobarn, corresponding to proton-proton collisions at $\sqrt{s} = 14$ TeV. Further details on the cuts can be found in the text.

Sample	Lepton cuts	WBF cuts	$m_{T,3l}$
$WZ+$jets	2.20	0.61	0.47
$t\bar{t}+$jets	0.013	0	0
$m_{W',Z'} = 700$ GeV, $\alpha = 0.9$	2.58	0.75	0.59
$m_{W',Z'} = 1000$ GeV, $\alpha = 0.9$	2.32	0.67	0.51
$m_{W',Z'} = 1500$ GeV, $\alpha = 0.9$	2.22	0.63	0.48
$m_{W',Z'} = 2000$ GeV, $\alpha = 0.9$	2.23	0.63	0.48
$m_{W',Z'} = 700$ GeV, $\alpha = 0.5$	4.01	1.22	1.06
$m_{W',Z'} = 1000$ GeV, $\alpha = 0.5$	2.82	0.84	0.68
$m_{W',Z'} = 1500$ GeV, $\alpha = 0.5$	2.40	0.69	0.54
$m_{W',Z'} = 2000$ GeV, $\alpha = 0.5$	2.31	0.66	0.50

experimental systematic uncertainties [see Fig. 3(c)]. However, this channel remains a "golden channel" for an additional isoscalar resonance, and the comparison to WW and WZ analyses will allow us to reach a fine-grained picture of the involved dynamics if resonances are discovered in either of the aforementioned channels.

D. Projections for $3l + \not{E}_T + jj$ production

The $3l + \not{E}_T + jj$ "interpolates" between the previous analyses. There is no pollution from gluon fusion events (even if we allow a significant coupling of Z' to the fermion sector). Additionally, the major backgrounds of the $2l + \not{E}_T + jj$ can be completely removed through the requirement of exactly three isolated leptons with $p_{T,l} > 15$ GeV, with no charge requirement. We then require the cuts given in Eqs. (4) and (5) and for the lepton and WBF selection, respectively. The signal is extracted following a final selection $m_{T,3l} > 350$ GeV, where

$$m_{T,3l}^2 = \left[\sqrt{m_{l_1 l_2 l_3}^2 + p_{T,l_1 l_2 l_3}^2} + |p_{T,\mathrm{miss}}|\right]^2 - [p_{T,l_1 l_2 l_3} + p_{T,\mathrm{miss}}]^2. \qquad (7)$$

The results are collected in Table III.

Although a substantial amount of missing energy is present, the lepton-$\not{E}_T$ system is highly correlated in this final state, allowing for recovery of most of the mass discrimination through Eq. (7), see Fig. 3(c).

As a result of the nonstandard Higgs coupling, a large enhancement of the signal strength is present. This can be seen compared to the Standard Model background in Fig. 4.

E. Setting limits with $3l + \not{E}_T + jj$ production

Combining the analyses of the previous sections, we can see that the potential presence of new vector resonances for $\sim$10% Higgs coupling deviations can be highly constrained with the $3l + \not{E}_T + jj$ channel. Although we believe that more advanced limit setting procedures that deal with full

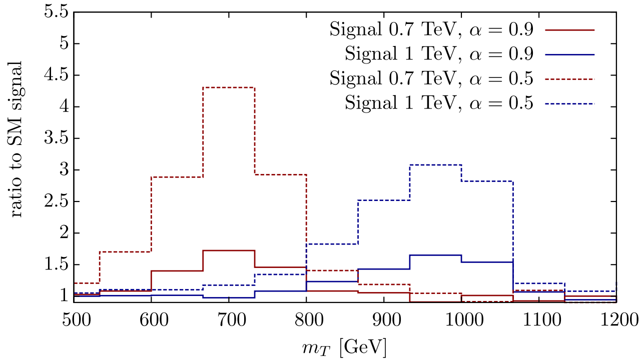

FIG. 4 (color online). Ratio of the BSM differential cross section in $pp \to W^{\pm}Zjj \to 3\ell \not{E}_T jj$ in comparison with the SM WBF distribution. Shown are different values $\alpha = 0.5,\ 0.9$; widths are chosen as 3 GeV, 7 GeV, 10 GeV and 30 GeV, respectively.

correlations can eventually be used to constrain isotriplet states in the $2l + \not{E}_T + jj$ and $4l + jj$ final states, the $3l + \not{E}_T + jj$ provides the most direct avenue to constrain such a scenario.

We thus quote an expected significance using $3l + \not{E}_T + jj$ final states (Sec. II D) on the basis of mass, width and modified Higgs coupling strength in Figs. 5(a) and 5(b). The signal extraction is performed over a mass window of $0.3 \times m_{W'}$ in the transverse mass equation (7). The calculated significance follows from

$$\mathcal{S} = \frac{N(\text{BSM}) - N(\text{WBF, SM})}{\sqrt{N(\text{bkg, non-WBF}) + N(\text{WBF, SM})}}, \qquad (8)$$

where the individual N's refer to the signal counts at a given luminosity. Using this measure we can isolate a statistically significant deviation from the SM WBF distribution outside the Higgs signal region, taking into account the irreducible background in the WZ channel.

Already for a target luminosity of run 2 of 100/fb, a large parameter region can be explored in the $3l + \not{E}_T + jj$ channel. A crucial parameter in this analysis is the width of the additional resonance, which we take as a free parameter in our analysis. With an increasing width the signal decouples quickly, but stringent constraints can still be formulated at a high-luminosity LHC, especially if new physics gives rise to only a percent-level deformation of the SM Higgs interactions, see Fig. 6. Note that the signal decouples very quickly with an increased value of the width. Hence, if there in scenarios where the extra vector bosons have a large coupling to the top as expected in some composite models, the sensitivity in the WBF search might not be sufficient to constrain the presence of such states. It is worthwhile to stress the complementarity of the WBF searches as outlined in the previous sections to the aforementioned Drell-Yan-like production in this regard. Both ATLAS and CMS have published limits of searches for W' and Z' resonances in third quark generation final states [36–39]. If the states we investigate in this paper have a sizable coupling to massive fermions, these searches will eventually facilitate a discovery. In this case, however, the search for WBF resonances still provides complementary information about the nature of electroweak symmetry breaking. In particular WBF production will act as a consistency check of the excesses around 2 TeV seen by CMS and ATLAS [40,41].

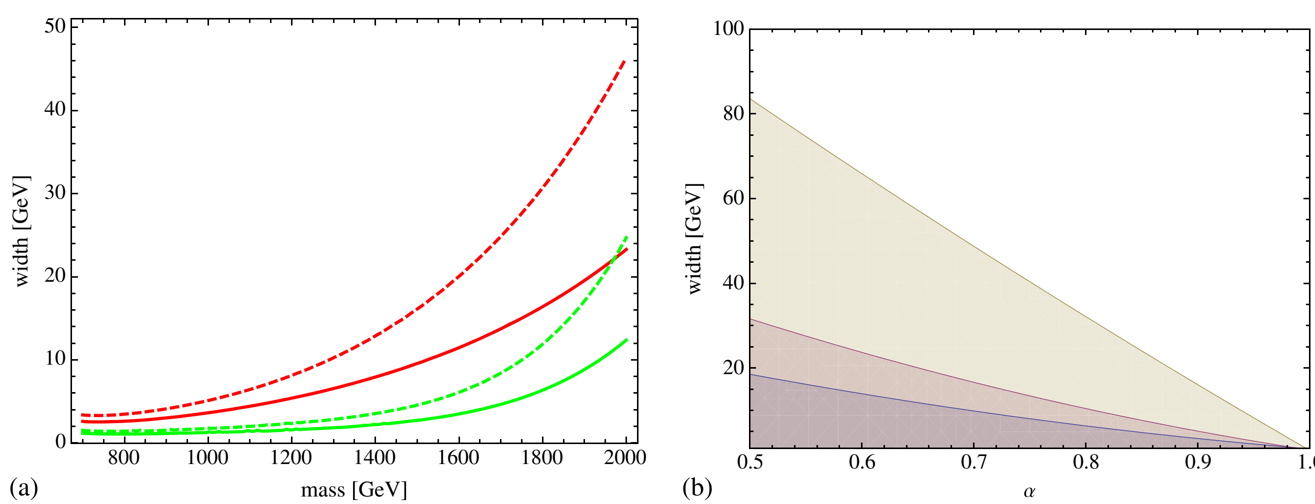

FIG. 5 (color online). Projections of the $3l + \not{E}_T + jj$ analysis for a small integrated luminosity of 100/fb. (a) 95% condfidence level (dashed) and 5σ discovery (solid) contours in the mass-width plane of the $3l + \not{E}_T + jj$ analysis for an integrated luminosity of 100/fb and $\alpha = 0.9$ (red) and $\alpha^2 = 0.9$ (green); (b) 95% condfidence level exclusion contours for 700 GeV (blue), 1000 GeV (red) and 1500 GeV (yellow) for a nominal luminosity of 100/fb.

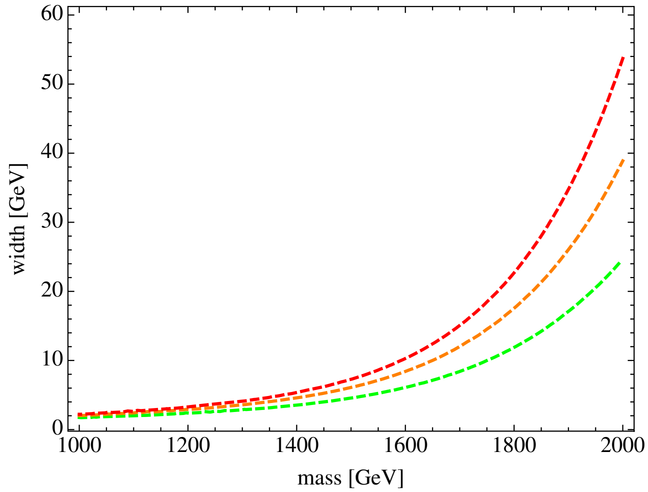

FIG. 6 (color online). Projections of the $3l + \not{E}_T + jj$ 95% confidence level contours for 100/fb (green line), 500/fb (orange line) and 3000/fb (red line). The Higgs coupling deviation is $\alpha^2 = 0.95$.

III. SUMMARY AND CONCLUSIONS

The search for new physics interactions after the discovery of the Higgs boson remains one of the main targets of the LHC. Current constraints on Higgs couplings inferred from run 1 signal strength measurements, in particular in the ZZ channel, leave a lot of space for the appearance of new resonant phenomena at the TeV scale. These can, but do not necessarily have to be, isoscalar degrees of freedom. To this end we have combined the observation of a SM-like Higgs boson with the appearance of new isovectorial degrees of freedom at the TeV scale. These are further corroborated by small excesses in similar and recent searches during run 1 [18]. Solely based on probability conservation, we provide predictions for the weak boson fusion channels, which are theoretically well motivated candidate processes to study resonant phenomena connected to unitarity and the anatomy of electroweak symmetry breaking. Our approach of saturating W, Z unitarity sum rules with a single set of vector resonances as a function of vector boson mass and Higgs coupling deviation provides a complementary approach to singlet-extended Higgs sectors with a highly modified TeV-scale LHC phenomenology.

While resonances and continuum excesses due to new t- and u-channel contributions and a smaller destructive Higgs contribution at large multilepton mass might be challenging to observe in $2l + \not{E}_T + jj$ and $4l + jj$ production, we have shown that an analysis of $3l + \not{E}_T + jj$ production provides an excellent avenue to constrain or even observe the presence of such states over a broad range of mass and width scales. With comparably low integrated luminosity at the LHC, such an analysis captures complimentary and necessary information to pin down the very character of new physics for small deviations of the Higgs on-shell phenomenology, especially when results across the different WBF channels are combined.

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