Observing nonstandard $W'$ and $Z'$ through the third generation and Higgs lens

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Abstract

We reinterpret $W'$, $Z'$ and Higgs searches at the LHC in terms of a model with nonuniversal $V'$ couplings to fermions in order to gauge how well these searches can be applied outside the (simplified) scenarios for which they were optimized. In particular, we consider bounds from $V'$ searches in final states $\tau\tau$, $e\nu$, $ll$ and $tb$, and discuss the impact of width effects. We then show that decays of the type $V' \to Vh$ yield additional bounds on the heavy vector masses and, in the case of a discovery, provide an important probe of the heavy sector. Finally, we match the low energy limit of the model to an effective theory and compare the bounds on the resulting dimension-6 operators with the direct searches discussed in this paper.
1 Introduction

Heavy vectors, either in the form of new gauge bosons or as composite resonances, are a feature of many BSM scenarios such as composite Higgs models, GUTs with extra $U(1)$ gauge groups, $LR$-symmetric models or models with extra dimensions. Searches at the LHC for “classical” heavy gauge vectors often consider the sequential Standard model (SSM) case where a $W'$ or $Z'$ are present with a large mass but couplings identical to the known electroweak bosons. The SSM-like $W'$ with righthanded couplings allows for a somewhat simplified analysis as interference with the SM $W$ is eliminated. In the case of the $Z'$, there are some typical anomaly-free candidate charge assignments inspired e.g. from $B-L$ symmetry or $E_6$ GUTs which differ somewhat from the SSM case, and are subject to RG running [1, 2].

The family $SU(2)_1 \times SU(2)_2$ model [3] on which we focus here is another possible setting for heavy vector resonances beyond the SSM case, and it contains an extended Higgs sector charged under the extended gauge group. The model is of interest for several reasons: it is being used by CMS as a theory motivation and testing ground for upcoming searches involving third generation fermions. It provides a concrete realization of enhanced third generation couplings to the heavy sector. Since family- nonuniversal gauge groups are strongly constrained from flavor physics, it is useful to know when the reach of the LHC can beat indirect constraints in such models. Furthermore, while featuring a SM-like light Higgs by design, as we point out, the structure of the extended Higgs sector is revealed through interactions with the heavy gauge bosons even when the physical heavy Higgs bosons are out of reach of the LHC. We use the opportunity to compare the description of anomalous Higgs interactions via dimension-6 operators to the low-energy limit of an explicit model, and compare the sensitivity of the two approaches and its dependence on the underlying physics.

This paper is organized as follows: In section 2 we briefly describe the model given in [3], and provide the Feynman rules needed for our analyses. We discuss in particular the (heavy) Higgs sector and its influence on the $V'$ phenomenology. In section 3, we revisit existing LHC searches for heavy vectors, apply them to the $SU(2)_1 \times SU(2)_2$ model where possible and discuss the issues with the interpretation of shape-based versus single-bin analyses. In section 4 we repurpose existing Higgs searches in $Vh$ associated production final states and derive bounds on $V'$ from $V' \rightarrow Vh$ decays. We briefly discuss simple ways how these searches can be optimized to greatly enhance their reach. Finally, we contrast direct searches in the Higgs channel with indirect bounds on EFTs. We conclude in section 5.

2 The Model

The model which we consider is identical to the one introduced in [3]. We only briefly revisit the basics and some aspects of particular importance to this work, and refer the reader to the original paper for a more thorough discussion. There is an $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ electroweak gauge group with couplings $g_1 = g/\cos(\theta_E), g_2 = g/\sin(\theta_E), g'$ which is broken down to $SU(2)_L \times U(1)_Y$ with couplings $g, g'$ by a bifundamental scalar $\eta \sim (2, 2)$. The latter can be chosen to be selfdual in the sense that $\epsilon_{\beta \alpha} \epsilon_{\beta' \alpha'} \eta^{\alpha \alpha'} = \eta_{\beta \beta'}$, thus eliminating all degrees of freedom besides a (heavy) neutral Higgs scalar $h'$ and three would-be Goldstone bosons for
the heavy vectors $X^{0,\pm}$:

$$
\eta = \begin{pmatrix}
u + \frac{k^g + iX^0}{\sqrt{2}} & \frac{X^+}{\sqrt{2}} \\
-\frac{X^-}{\sqrt{2}} & u + \frac{k^b - iX^0}{\sqrt{2}}
\end{pmatrix}
$$

(1)

where we have assumed that $\eta$ develops a vev $\langle\eta\rangle = uI_{2\times 2}$, and normalize the fields to a kinetic term $Tr[D_\mu \eta^\dagger D^\mu \eta]$. There are two Higgs doublets $\phi_1 \sim (2,1)_{\frac{3}{2}}$ and $\phi_2 \sim (1,2)_{\frac{1}{2}}$ charged under $SU(2)_L$ and $SU(2)_R$ respectively. In analogy to other 2HDMs, they are set up to have vevs $v_1$ and $v_2$ where as usual, $\tan \beta = v_2/v_1$. The authors of [3] introduce a small quantity $\epsilon = v/\sqrt{2}u$ which allows to expand effects in leading powers of $\epsilon$. Unlike standard 2HDMs, here $\phi_1$ bestows masses to the first two generations, whereas $\phi_2$ does the same for the third generation. Hence, a large $\tan \beta \gg 1$ can explain the relative smallness of masses in the first two generations compared to the top, whereas it does not explain the hierarchy $m_b \ll m_t$. This is in contrast to the MSSM or Type II models where $\tan \beta \gg 1$ can explain the hierarchy $m_b \ll m_t$, but not $m_u, m_c \ll m_t$. This division of labor for the $\phi_i$ requires the left handed fermions from the first two generations to be doublets under $SU(2)_L$, whereas those in the third are doublets under $SU(2)_R$. Consequently, the covariant derivatives for the matter and Higgs fields are given by

$$
D_\mu \phi_i = \left[ \partial_\mu - ig_i W^a_{\mu} T^a - ig'\frac{1}{2} B_\mu \right] \phi_i

D_\mu \psi_{gen=1,2} = \left[ \partial_\mu - ig_1 W^a_{\mu} T^a P_L - ig'Y_f B_\mu \right] \psi_{gen}

D_\mu \psi_{gen=3} = \left[ \partial_\mu - ig_2 W^a_{\mu} T^a P_L - ig'Y_f B_\mu \right] \psi_{gen}

D_\mu \eta = \partial_\mu \eta - ig_1 W^a_{\mu} T^a \eta + ig_2 W^a_{\mu} \eta T^a.

(2)

When $\eta$ develops the vev, only transformations $U_1 \eta U_2^\dagger$ with $U_1 = U_2 = U$ survive, where $U$ can be identified as elements of the SM group $SU(2)_L$. Due to nonabelian gauge invariance, this remaining light $SU(2)_L$ couples universally to all generations. Neglecting $O(\epsilon)$ mixing effects, the light and heavy gauge bosons $W_L, W_H$ are given by

$$
W^a_L = \frac{g_2 W^a_\eta + g_1 W^a_H}{\sqrt{g_1^2 + g_2^2}}, \quad W^a_H = \frac{g_1 W^a_L - g_2 W^a_H}{\sqrt{g_1^2 + g_2^2}}.

(3)

This approximation is sufficient for our purposes, since $O(\epsilon^2)$ effects such as $V' \rightarrow VV$ decays are subleading in our analyses. The $W^a_L$ couples with $B$ to form $\gamma, Z$ as usual.

The particle content of the two doublets is that of usual 2HDMs, and since we assume to be in the decoupling limit, pseudoscalar, charged and neutral Higgs mixing are all given by $\beta$,

$$
\phi_1 = \begin{pmatrix}
c_\beta G^+ - s_\beta H^+ \\
\frac{c_\beta}{\sqrt{2}} (v + h + iG^0) - \frac{s_\beta}{\sqrt{2}} (H + iA)
\end{pmatrix}

\phi_2 = \begin{pmatrix}
s_\beta G^+ + c_\beta H^+ \\
\frac{s_\beta}{\sqrt{2}} (v + h + iG^0) + \frac{c_\beta}{\sqrt{2}} (H + iA)
\end{pmatrix}

(4)

By definition, $\beta$ is chosen such that $G^+, G^0$ are the would-be Goldstone bosons of $W, Z$. In the full theory, $H^+$ and $A$ are not purely the physical heavy Higgs, but mix with $X^{0,\pm}$ to form the

\begin{itemize}
  \item \text{Note that we normalize the vev differently, with $\langle\phi_i^\dagger \phi_i\rangle = v_i^2/2$.}
\end{itemize}
Table 1: The Feynman rules relevant for $V'$ production and decay in the family-$SU(2)_1 \times SU(2)_2$ model. We assume that the heavy Higgs sector has masses $m_H$, $m_{h'} \gg m_{V'}$.

heavy sector would-be Goldstones. These mixings are however $\propto c_\beta s_\beta = s_\beta^2/\tan \beta$ and will not concern us for the remainder of this work where we consider large $\tan \beta$. Indeed, in the limit where $m_{A,H,H^+} > m_{V'}$, the interactions relevant for $V'$ searches all originate from the kinetic terms

$$L_{kin} = \sum_f \bar{\psi}_f D \psi_f + \sum_i D_\mu \phi_i^\dagger D^\mu \phi_i$$  \hspace{2cm} (5)

while decays of $V'$ to heavy Higgs particles are additionally governed by

$$L_{kin} = Tr[D_\mu \eta^\dagger D^\mu \eta].$$  \hspace{2cm} (6)

One interaction which has not been considered in [3, 4, 5] is the $V'Vh$ vertex which will be of particular interest later. For some regions of parameter space, it increases the width of the heavy vectors by up to 6%, and it yields an interesting phenomenology.

### 2.1 Feynman Rules for Production and Decay

The couplings of $W'$ and $Z'$ are purely left-handed in our approximation suitable for collider searches where we neglect $O(\epsilon)$ $Z - Z'$ mixing. Hence, while the $W'$ can be SSM-like, the $Z'$ is essentially $W'$-like and the three states form a near-degenerate $SU(2)_L$ triplet. This is also reflected in an identical total width. We are here mainly concerned with the vertices of $V'$ to SM fermions as well as the $V'Vh$ vertices. They are given in Table 1. As expected, the $Z', W'$ simply couple like an $SU(2)$ triplet. One finds that the $W'$ couplings become SSM-like (up to a sign in the third generation!) for $\tan E = \cot E = 1$ corresponding to $c_E = s_E = 1/\sqrt{2}$.

For $\tan \beta \gg 1$, the factor $s_E^2 - s_\beta^2$ in the $V'Vh$ coupling lets the Higgs and Goldstones behave like a partial fermion of the third generation because $s_E^2 - s_\beta^2 \rightarrow -c_E^2$, and as one of the first and second generation for $\tan \beta \ll 1$. In fact, the decays $V' \rightarrow Vh$ are dominated by
the longitudinal mode and can be approximated by $V' \rightarrow G^{0\pm} h$. In the limit $\tan \beta \gg 1$, $BR(Z' \rightarrow Zh) = \frac{1}{2} BR(Z' \rightarrow \tau \tau)$ and $BR(W' \rightarrow Wh) = \frac{1}{4} BR(W' \rightarrow \tau \nu \nu)$ if we neglect phase space factors. Consequently, observing these decays of the heavy vectors gives us information about the relative mixing angles in the Higgs and gauge sector. Since the $SU(2)$ triplet couples universally to all fermions of a generation, we can calculate the widths and branching ratios at tree level simply by counting degrees of freedom. Neglecting phase space factors, in the limit $\tan \beta \gg 1$,

$$\Gamma_{W'} = \Gamma_{Z'} = \Gamma_{SSM} W' \times \left(3 + 1 + \frac{1}{4} \right) \cot^2 E + (6 + 2) \tan^2 E \frac{12}{1 + \frac{1}{4}}. \quad (7)$$

Similarly, the branching fractions scale like $BR = BR_{SSM} \times \cot^2 E \Gamma_{SSM} / \Gamma_{W'}$ for 3rd generation fermions and $BR = BR_{SSM} \times \tan^2 E \Gamma_{SSM} W' / \Gamma_{W'}$ for 1st and 2nd generation fermions. The $q\bar{q}$ initiated production at LHC scales with $\tan^2 E$, while the branching into 3rd generation fermions scales as $\cot^2 E$. Neglecting phase space factors, the $V'$ production and decay into 3rd generation fermions thus scales as $\sigma \times BR \propto \Gamma_{SSM} W' / \Gamma_{V'}$. The $V'$ production with subsequent decay into 1st and 2nd generation fermions receives an additional factor $\sigma \times BR \propto \Gamma_{SSM} W' / \Gamma_{V'}$. For $\tan E > 1$, the production and decay into 1st and 2nd generation fermions is thus greatly enhanced, whereas for $\cot E > 1$, decays into 3rd generation fermions become important.

### 3 Limits from direct $Z'$ and $W'$ Searches

In searches for sequential SM-like $Z'$ or $W'$, channels involving $\tau$ leptons or top quarks are currently not particularly competitive. As we have just seen, this might change when family-nonniversal couplings are considered such as they appear in the $SU(2)_1 \times SU(2)_2$ model which we have briefly reviewed above (of course, once we relax the restriction to SM-like heavy vectors, we need information from all available channels anyhow in order to classify a newly discovered vector boson). We now extend the discussion of bounds on this model given in [5, 4] by recent searches and a discussion of model dependence. Indeed, the other crucial difference apart from the modified couplings is the modified width of the heavy vectors which can be significantly enhanced with respect to the sequential case (the respective widths are shown in Figures 1 and 2). This can render problematic any comparison with existing searches which are specifically performed or at least optimized for sequential SM-like vectors, or in general for particles with narrow width.

For example, a recent CMS search presented in [6] for $W' \rightarrow tb$ decays in lepton+jets, which to date is the most sensitive analysis for this channel, uses a shape-based Bayesian analysis. While the quoted limit including interference effects of $M(W') > 1.84$ TeV (improving to $M(W') > 2.05$ TeV without interference) can be interpreted in terms of an upper bound on $BR \times \sigma$, it is not obvious how this bound changes when realistic widths are taken into account. Since the analysis is too intricate to redo, we limit ourselves to naively scaling the bound on $BR \times \sigma$ for the sequential case according to the modified couplings and branching ratios in the

\footnote{Oddly, in [5, 4], the authors consider the limit $\tan \beta \rightarrow 0$, which is not theoretically feasible, especially without completely changing the remaining phenomenology of the model. Fortunately, the $V'$ searches are only weakly affected by this choice.}
nonuniversal model. The result is shown in Figure 1 (red dashed). Note also that interference effects will be influenced by the relative sign of $W$ and $W'$ couplings, which is reversed in the model we consider here and could lead to a further enhancement. It would therefore be interesting to know the exclusion including interference effects of either sign, and for general widths.

For $\cot E \gtrsim 2$, the limits from $W' \rightarrow tb$ become more sensitive than the $Z' \rightarrow ll$ search presented in [7], which we have similarly scaled to accommodate modified couplings and branching ratios (see Figure 1 blue dashed).

Figure 1: Limits from $W' \rightarrow tb$ (red dashed) [6], $Z' \rightarrow ll$ (blue dashed) [7] from naive scaling. The gray dashed lines give the width of the W'/Z' in GeV. The gray solid lines denote the regions where $e^2 < 0.15, 0.1$ (from left to right)

The CMS search in $Z' \rightarrow t\bar{t}$ [8] in principle profits from the enhancement of third generation couplings, but is currently not competitive with other final states in the model under consideration.

Two further searches, $Z' \rightarrow \tau\tau$ [9] and $W' \rightarrow e\nu$ [10], are based on a single-bin analysis using an $M_T^{\min}$ cut. An $M_T$ cut is chosen depending on the signal mass hypothesis in order to optimize the expected $S/B$ in the case of a sequential $Z'$ and $W'$. Since the quoted limits are in principle sensitive to width effects, we have implemented these searches into ROOT, and simulate $W'$ and $Z'$ production using MadGraph 5 [11]/Pythia [12]/Delphes [13] using our FeynRules [14] [15] implementation of the $SU(2)_1 \times SU(2)_2$ model. We have then determined the relative acceptances of the $M_T$ cut in the nonuniversal model compared to the sequential case, and rescale the limits accordingly. The results (solid) are shown in Figure 2 in comparison with the naively scaled limits (dashed). We find that in the region of enhanced width, the discrepancy is $\gtrsim 100$ GeV in the case of the $Z' \rightarrow \tau\tau$ final state, and as expected, the naively scaled result somewhat overestimates the exclusion power. The effect in the $Z' \rightarrow ll$ search is
less pronounced, which was to be expected since the sensitivity drops off quickly for $\cot E > 1$, and the widths in the excluded region therefore stay below $\lesssim 100$ GeV. While it is probably unavoidable that in the case of increased width, $S/B$ decreases, the $M_T^{\text{min}}$ cuts used in these searches could still be optimized for different widths, which would potentially improve their sensitivity to non-sequential vectors.

In fact, a CMS search for $W' \to \tau \nu$ is in preparation which takes this effect into account by optimizing the signal mass dependent $M_T^{\text{min}}$ cuts using the widths suggested by the family-$SU(2)_1 \times SU(2)_2$ model. It has the potential to yield the strongest bound in the region $\cot E > 1$.

Figure 2: Limits from $Z' \to \tau \tau$ (left) [9] and $W' \to e\nu_e$ (right) [10]. The blue dashed lines show the limits from naive scaling of SSM crosssection, the blue solid lines show the limit after applying the analysis (and correcting for the SSM-acceptance). The gray dashed lines give the width of the $W'/Z'$ in GeV. The gray solid lines denote the regions where $\epsilon^2 < 0.15, 0.1$ (from left to right).

4 Limits from Higgs Searches

There are two obvious ways in which heavy vectors could contribute to a signal in “Higgsstrahlung” type searches. There could be radiation of a Higgs off a $V'$,

$$pp \to V^*, V'^* \to V'h,$$

While this paper was in preparation, [17] came out which uses Higgs searches in order to constrain composite Higgs scenarios. Repurposing Higgs searches for $V'$ searches has been suggested for example in [18, 19].
followed by suitable $V'$ decay modes, or resonant $V'$ production with subsequent decay,
\[ pp \rightarrow V' \rightarrow Vh. \]

The former process is strongly suppressed by the $V'$ mass, and due to the background-like kinematic configuration (back-to-back $V'$ decay products and a soft Higgs), the Higgs searches which we consider here are not sensitive to it. The latter process on the other hand is equivalent to standard $V'$ production, and in the model under consideration, merely suffers from a somewhat reduced branching fraction due to the factors $\frac{1}{2}$ or $\frac{1}{4}$ relative to $V' \rightarrow ff$. Furthermore, its kinematics are identical to the high-$p_T$ tail of conventional SM associated Higgs production, and acceptance of selection cuts is in principle excellent. We now concentrate on the search in ATLAS for Higgs associated production in final states with two $b$-jets, leptons and missing energy [20] which are designed for production processes
\[ pp \rightarrow Zh; \ h \rightarrow \bar{b}b, Z \rightarrow \ell\ell, \nu\nu \]
\[ pp \rightarrow W^{\pm}h; \ h \rightarrow \bar{b}b, W^{\pm} \rightarrow \ell\nu/\ell\bar{\nu}. \quad (8) \]

This ATLAS search was recently discussed in the context of EFTs precisely for its sensitivity to high-$p_T$ effects [21, 22] which we want to exploit here as well. We have implemented the corresponding ATLAS searches [20] into ROOT, and simulations are again performed using MadGraph/Pythia/Delphes using our FeynRules implementation of the $SU(2)_1 \times SU(2)_2$ model. The analyses of Ref. [20] use 5 (2$\ell$ and 1$\ell$) or 3 (0$\ell$) different $p_T(V)$ bins separated at $p_T(V) = (0-90, 90-120, 120-160, 160-200, > 200 \text{ GeV}$ which are subject to different additional kinematic cuts. In the case of heavy vectors decaying like $V' \rightarrow h + V \rightarrow \bar{b}b + \ldots$, virtually all signal events from onshell production fall into the highest-$p_T$ bin. For $m_{V'} > 400 \text{ GeV}$, the search as it is performed is thus not very sensitive to the width of the heavy vector. The overall sensitivity is however reduced by only using the leptonic decay modes of the $W, Z$. While this is sensible for SM Higgs production, sensitivity to $V'$ production might be improved in this high-$p_T$ region by using dedicated searches in $bb$ + jets final states, where one can additionally exploit the fact that $m_{bb} \approx m_h$. However, let us press on to see how far we get by using the existing data in the leptonic final state. For different values of $\tan\beta$, $\sigma \times BR$ scales (up to PS factors) like $V'$ production and subsequent decay to third generation fermions which was discussed before.

The acceptance for the three classes of final states improves for masses $m_{V'} \gg m_V$, reaching $\approx 25\%$, but deteriorates for $m_{V'} \gtrsim \text{TeV}$ due to decreasing angular separation of the two jets originating from a boosted Higgs. We use the 70% b-tagging efficiency which is specified in the ATLAS search throughout the energy range, which may be a source of additional uncertainty. Furthermore, we add the 2-jet and 3-jet tagged events for simplicity. Knowing the number of observed events, expected background, background error and expected SM Higgs signal in the three overflow bins, we calculate the $\Delta \chi^2$ in the presence of an additional $V'$ signal for a given mass. Note that we use the SM Higgs signal as a background. Although there is a slight underfluctuation in the 2-lepton final state, the best fit point is approximately given for $m_{V'} \rightarrow \infty$. The resulting limit is shown in Figure 3. We have not included $K$-factors here, which are usually $\gtrsim 1$ for $W', Z'$ production and could further enhance the sensitivity slightly. While this limit is not very strong compared to dedicated $V'$ searches, it is noteworthy that it
can be obtained with existing published Higgs data. Of course, having the signal events in one 
overflow bin together with all $p_T^{V'} > 200$ background events is hopelessly conservative for our 
analysis. Sensitivity could obviously be improved by imposing optimized $p_T^{V'}$ cuts for each 
signal mass hypothesis $m_{V'}$ in analogy to the variable $M_T^{\min}$ cuts used for the $W'$ and $Z'$ searches 
discussed above. In order to do this, we need to know the $p_T$ shape of relevant backgrounds 
after cuts. Of course, by optimizing this $p_T^{V'}$ cut for maximal expected S/B, we once again gain 
sensitivity to the total width, and again, experimental analyses should ideally take this into 
account in order to be applicable to a wide range of $V'$ models. To obtain an estimate what the 
actual limits on such $V'$ searches are, we have a closer look at the backgrounds. The 1-lepton 
channel by itself yields the strongest limits, and its background is dominated by top production, 
in particular $tt$ decaying semileptonically. We simulate the process at LO (+radiation of a hard 
jet) using MG5/Pythia/Delphes as we did with the signal, and perform the $Vh$ analysis, but 
with different choices of $p_T^{V'}$ cutoff. We are particularly interested in the mass scale where no 
or few background events are expected. We find that the background from $tt$ production yields 
$O(1)$ events for $p_T^{V'} > 400$ GeV. A naive estimate of significance from Poisson statistics suggests 
that for $S \geq 3$ expected events, no observation corresponds to $p \leq e^{-3} \sim 0.05$. To estimate the 
potential exclusion power, in Figure 3 we have marked the parameter regions with 3, 5 and 10 
expected events in the 1-lepton search for $W'$ production. These numbers will still be subject 
to the $p_T^{V'}$ search cut. While the majority of events from the decay will have $p_T^{V'} \sim M_{V'}/2$ and 
thus lie in a region with negligible SM+Higgs background, there is a suppressed tail towards 
smaller values. However, for a $2p_T^{V',\min} \ll M_{V'}$, only a small percentage of events are cut away. 
For example, for $p_T^{V',\min} = 400$ GeV and $M_{V'} = 1700$ GeV, we find an acceptance after all other 
cuts of $A(p_T^{V',\min}) \sim 90\%$. A complete experimental analysis of the data with all backgrounds, 
generalizing the Higgs searches in associated production and fully exploiting the known invariant 
mass of Higgs decay products, would be an interesting endeavour.

The description of BSM effects using 59 dimension-6 operators [24] relies on a minimal 
flavour violation (MFV) scheme. In this framework, the leading BSM effects affecting only 
Higgs physics and triple gauge couplings (TGCs) can be described by (depending on how one 
counts) 10 operators [20, 25]. Models with nonuniversal couplings to fermions such as the one 
discussed here require an extension of this basis. Even in the “universal” limit $\tan B = 1$, the 
model predicts a relative sign between the 3rd generation $V'$ couplings and the others, spoiling 
an exact matching to the MFV operator basis. However, we can make a quantitative comparison 
as long as we are dealing with couplings of the $V'$ to 1st and 2nd generation fermions, as is the 
case in this Higgs search. In our case, the relevant couplings corresponding to the Feynman 
rules given above are  
$$iL = \frac{g}{\sqrt{2}} \pi \gamma^\mu P_L d W^{\tau+}_\mu - \frac{1}{2} g^2 \phi^\dagger \phi W^{\tau-}_\mu W^{+\mu}$$  
(9) 
where $\phi$ denotes the light SM Higgs doublet. Integrating out a $W'$ of mass $M$ at tree level 
amounts to putting the propagator $ig^{\mu \nu} / M^2$ between the two dim-4 operators, resulting in a 
dimension-6 interaction  
$$iL_{eff} = \frac{g^3}{2 \sqrt{2} M^2} \phi^\dagger \phi (\pi \gamma^\mu P_L d) W^{+\mu}_\mu.$$  
(10)
Due to gauge invariance, this interaction can be mapped to a term

$$\mathcal{L}_{\text{eff}} = \frac{g^2}{4M^2} i(\phi^\dagger \sigma^a \overleftrightarrow{D}_\mu \phi) \overline{Q}_L \sigma^a \gamma^\mu Q_L$$  \hspace{1cm} (11)$$

in the Lagrangian. It can be eliminated for the first two generations by performing a field redefinition

$$W^a_\mu \rightarrow W^a_\mu - \frac{g}{2M^2} i \phi^\dagger \sigma^a \overleftrightarrow{D}_\mu \phi$$  \hspace{1cm} (12)$$

which generates

$$\Delta \mathcal{L} = \frac{1}{M^2} \frac{ig}{2} (\phi^\dagger \sigma^a \overleftrightarrow{D}_\mu \phi) D_\nu W^{a \nu \mu} \equiv \frac{1}{M^2} \mathcal{O}_W$$  \hspace{1cm} (13)$$

as well as $2\mathcal{O}_H - 4\mathcal{O}_r = (\phi^\dagger \sigma^a \overleftrightarrow{D}_\mu \phi)^2$ at dimension-6 level\footnote{Note that the same operator $\mathcal{O}_H - 2\mathcal{O}_r$ is already generated upon integrating out $W''$, $Z'$, but enhanced with $\cot^2 E$. It rescales the Higgs couplings and becomes an important effect in the $\cot E \gg 1$ regime. A detailed analysis of this effect is subject for future research, and will not concern us for the comparison at hand which focuses on the effects of $\mathcal{O}_W$.} and an additional term of the form Eq. (11) for the 3rd generation which will cancel the effect of $\mathcal{O}_W$. We can thus identify the mass of our heavy vectors with the Wilson coefficient

$$\frac{1}{M^2} \sim c_W/m^2_H$$  \hspace{1cm} (14)$$

in the basis of [26] at least as long as we consider currents of 1st and 2nd generation fermions. This operator contributes to the $S$ parameter as well as TGCs and Higgs production. The bounds on the combination of operators $\mathcal{O}_W - \mathcal{O}_B$ in associated Higgs production were analyzed in [21], and since we have used the same ATLAS analysis here to obtain bounds on resonant vector production, we can make a direct comparison. For the point $\cot E = 1$, the combined exclusion in the unmodified Higgs search is at $M \gtrsim 1300$ GeV. This translates to a model-dependent limit on the Wilson coefficient of $|c_W| \lesssim 0.0038$, which is already significantly smaller than the limits obtained from EFT analyses of $-0.04 < c_W < 0.01$. Our estimate for the achievable limit (with current data) in a Higgs search with optimized $p_T$ cuts lies closer to $M \gtrsim 1700$ GeV, which corresponds to $|c_W| \lesssim 0.0022$. The existing $W'$ searches for leptonic final states yield $M \gtrsim 3000$ GeV, corresponding to $|c_W| \lesssim 0.00072$. These EFT analysis in [21] considers the combination $c_W = -c_B$ in order to probe a direction orthogonal to the $S$ parameter, which might modify the bound somewhat. However, the interpretation of our comparison is not obvious for yet a different reason. Assuming an underlying model of the weakly interacting type discussed in this paper, bounds of the order of $-0.04 < c_W < 0.01$ in the EFT can only be obtained by using the EFT beyond its actual range of validity: near the resonance, dimension-8 operators e.g. of the type

$$\mathcal{O}_{\mathcal{O}W} = \frac{ig}{2} (\phi^\dagger \sigma^a \overleftrightarrow{D}_\mu \phi) D^2 D_\nu W^{a \nu \mu}$$  \hspace{1cm} (15)$$

are present from the higher orders in the $p^2$ expansion of the propagator. In order to be self-consistent in the presence of a weakly-interacting UV completion, the EFT needs to be cut off...
Figure 3: The limit (solid black) on family-$SU(2)_1 \times SU(2)_2$ model $W'$ and $Z'$ production at the LHC which we obtain from ATLAS searches\cite{20} for $Vh$ associated production using 7 and 8 TeV data. The yellow dotted, red dotted-dashed and blue dashed contours show the parameter values for 10, 5, 3 expected events in the 1-lepton channel respectively.

below the scale $m_W/\sqrt{|c_W|}$. This reduces its exclusion power to $c_W < 0.01$ (observed due to an underfluctuation, no lower limit possible), and no expected limit at all in either direction\cite{21}. Wilson coefficients $c_W \sim -0.04, 0.01$, if interpreted within our model, furthermore correspond to unrealistically low mass scales of $M_{Z'} \sim 400 \ldots 800$ GeV. The need to cut off the EFT at such low scales is unfortunate, considering that even using the EFT up to the unitarity bound yields a very conservative limit. In our example, the price of model-independence is thus still very high with current data.

This discrepancy between the two approaches is not surprising, as the EFT precisely throws away the resonant part of the propagator, only working with the constant offshell tail at dimension-6 level. The two approaches should converge in sensitivity for very strongly interacting vectors with large widths, for which the low-energy effective description nearly saturates the perturbative unitarity bound. We can observe this effect already here. Indeed, in the model at hand, we can increase $\cot E > 1$, i.e. $\sin E < 1/\sqrt{2}$, which raises the gauge coupling $g_2$. Interestingly, while this soon reduces the $\sigma \times BR(pp \rightarrow V' \rightarrow Vh)$ due to the $\cot^2 E$ suppression of the $\eta q$ initiated production, it leaves the corresponding Wilson coefficient for the dimension-6 coupling in Eq. (11), which is proportional to $\cot E \tan E / M^2$, unchanged. The sensitivity of the direct search in this channel is thus reduced, while the sensitivity of the EFT analysis remains the same. A similar effect can occur in the strongly-interacting light Higgs (SILH) model\cite{27} also considered in \cite{21} (in particular the case without composite fermions), where the respective dependences on the strong coupling $g_s$ and $g_s^{-1}$ of the $W' - W$ mixing and the Higgs coupling

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cancel. There, the comparison is more straightforward since it extends to all generations universally, and will be subject to future work. This property of the EFT can be seen from the perspective of the full theory: the relative enhancement of the offshell tail due to the increased width compensates the reduced coupling. For a simple weakly interacting heavy sector, the EFT approach is however still very conservative for existing LHC Higgs data. This will in principle change with large luminosity when offshell contributions to distributions can be measured more accurately while associated resonances are out of reach.

5 Conclusions

Heavy vector resonances are a well-motivated feature of many extensions of the SM, and various searches for them are being performed at the LHC. While many searches concentrate on scenarios in which \( W' \) and \( Z' \) share the same couplings as their SM counterparts (the sequential SM case), and relative widths are assumed to be small at around \( 3\% \), there exist well-motivated extensions of the SM which feature \( W' \) and \( Z' \) with differing properties. As an example, we have revisited a family-nonuniversal \( SU(2)_1 \times SU(2)_2 \) model[3]. Depending on the mixing angle of the extended gauge sector \( \cot E = g_2/g_1 \), the model features family-nonuniversal couplings of SM fermions to the \( W' \) and \( Z' \). While searches in channels involving third generation fermions are generally less sensitive in the sequential SM-like case, this situation changes for \( \cot E > 1 \) where couplings to the third generation are enhanced and all others suppressed. We have therefore reinterpreted the limits from ATLAS and CMS searches \( W' \to tb \) [6], \( W' \to vl \) [10], \( Z' \to \ell \ell \) [8], \( Z' \to \ell \ell \) and \( Z' \to \tau \tau \) [9] in terms of the family-nonuniversal model. We find that in large regions of parameter space, searches involving decays to third generation fermions are indeed competitive. However, enhanced third generation couplings also lead to an enhanced width, which complicates a reliable comparison with the published searches. While we can only give naively scaled limits for the shape-based analysis in [6], we have implemented the \( M_{T\text{min}} \) based single-bin searches in [9] and [10] in order to determine the acceptance of the \( M_{T\text{min}} \) cuts. We find that width effects can lead to a significant \( O(100) \) GeV overestimation of the exclusion power. Furthermore, interference effects are model dependent. For example, [6] find a \( \sim 200 \) GeV weaker limit when interference effects with single top production are taken into account. Since the model we consider here features a relative sign between \( W \) and \( W' \) couplings to the third generation, this effect might potentially enhance the sensitivity of this search further. In parameter regions of very large \( \cot E \) where \( \bar{q}q \) initiated production of \( Z' \) is strongly suppressed, it becomes interesting to consider \( pp \to \bar{b}bZ' \) associated production. We leave the analysis of this channel to future research.

In the last section, we have repurposed Higgs searches[20] in vector boson associated production \( pp \to Vh \to \bar{b}b + 0l, 1l, 2l \) to obtain limits on \( Z' \) and \( W' \) production. This channel is of particular interest to us here because it is sensitive to the Higgs sector mixing angle via \( g_{VVh} \propto s_E^2 - s_\beta^2 \) even when the heavy Higgs particles are out of reach of the LHC. Indeed, for large \( \tan \beta > 1 \), the \( V'Vh \) couplings are enhanced along with those of the third generation. Using the unmodified Higgs search, we find a lower bound \( M_{Z'}^2 = M_W' > 1300 \) GeV, corresponding to a bound on the Wilson coefficient \( |c_W| < 0.0038 \). However, we have argued that this limit can be improved considerably by employing additional optimized \( p_T \) and \( m_{bb} \) cuts for each signal mass hypothesis rather than collecting all high-\( p_T \) events in an overflow bin. In the parameter
region of interest, the reconstruction of highly boosted Higgs becomes crucial (see e.g. [23] for a recent analysis).

In a recent paper[21] it was argued that in the context of effective field theories, vector boson associated Higgs production ("Higgsstrahlung") is particularly sensitive to operators whose effects strongly grow with energy, such as $O_W$, $O_B$ in the notation of [26]. We have shown that in the low-energy limit, the family-$SU(2)_1 \times SU(2)_2$ provides an interesting testing ground for the effective theory approach, as the effects of $Z'$ and $W'$ can be matched to $O_W$ as well as some anomalous interactions for the third generation to which this search is not sensitive, thus allowing for a direct comparison. We find that in regions of parameter space where $g_1, g_2 < 1$, i.e. the weakly interacting regime, direct searches are much more sensitive than the effective theory approach which essentially discards the resonance. However, we observe that for $\cot E > 1$, the sensitivity of the direct search decreases, while the Wilson coefficient of $O_W$ remains essentially unaffected.

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