Scalar Hint from the Diboson Excess?

Aldo Deandrea
Université de Lyon, F-69622 Lyon, France; Université Lyon 1, CNRS/IN2P3, UMR5822 IPNL, F-69622 Villeurbanne Cedex, France
Institut Universitaire de France, 103 boulevard Saint-Michel, 75005 Paris, France

The possibility of testing the presence of new resonances in the Large Hadron Collider (LHC) data has attracted a lot of attention after the preliminary results indicating possible excesses in the Run 1 data by both ATLAS and CMS Collaborations in the diboson channels, including also the more recent diphoton excess at 750 GeV. In the following I discuss the possibility that a weak singlet pseudo-scalar particle, $\eta_{\rm WZ}$, decays into two weak bosons after being produced in gluon fusion at the LHC. The couplings to the gauge bosons arise in this case from a Wess-Zumino-Witten anomaly term which is calculable explicitly (not a free parameter) in models where the pseudo-scalar arises as a composite state, as the coefficients of the anomalous couplings can be related to the fermion components of the underlying dynamics. I provide simple examples of these composite realisations. When such hints will be tested in more detail in the Run 2 analyses of the LHC data it will be possible either to pinpoint in more detail the structure of the composite electroweak sector or to give bounds on it.

1 Introduction

The discovery of the Higgs boson at the LHC has confirmed the structure of the Standard Model (SM) in a remarkable way, but establishing a more fundamental theory of particle interactions is still an open question. Indeed the SM can be extended in order to explain in a more fundamental way the effective description we use today. Among the possible extensions for physics Beyond the Standard Model (BSM), I shall focus in the following on the possibility that new scalars couple to SM gauge bosons via a a Wess-Zumino-Witten (WZW) anomaly term. The hints suggested by the Run 1 data in the diboson channels can be easily accommodated in such a framework, as I will explain in the following. But on a more theoretical grounds, this possibility is a rather natural one when thinking of models with a composite dynamics (in terms of new fermions) for the electroweak sector. There are indeed two main reasons to suggest such a scenario: one of them is the explanation of the effective structure of the scalar sector of the SM in terms of pseudo-Goldstone dynamics or composite states or, more generally, as a mixing of the two. The second is more phenomenological as spin zero particles are typically among the lightest ones in this framework. If something can be learned from Quantum ChromoDynamics (QCD), is that allowing for fundamental fermions (the quarks) composite states of all sorts are possible as well as pseudo- Goldsone Bosons (PGBs). QCD is indeed a good example in this respect, containing in its spectrum the pions (PGBs), the sigma and the eta (composite scalars), the rho vector mesons (spin 1 composite states), axial-vector mesons, and the baryons (composite fermions).

In order to see the original motivation for the diboson channels excesses, I recall here the main experimental analyses that triggered this work [1]. The ATLAS search for resonant diboson ($WW/ZZ/WZ$) production in hadronic final states reported a discrepancy with respect to the background-only model with 3σ significance around 2 TeV [2]. A similar analysis was also performed by the CMS collaboration [3], where a moderate excesses, less than 2σ, was found in the same mass range $\sim$ 2 TeV. In the semi-leptonic decay channel however, no excess was observed [4,5] as well as in the fully leptonic channel of the WZ resonance [6,7].

More recently the ATLAS [8,9,10,11] and CMS [12] collaborations have started analysing Run 2 data and the new results neither confirm nor exclude yet the diboson signal, but give bounds in specific models. There is also a Run 2 ATLAS bound placing a 95% confidence upper limit on the di–jet cross-section at the level of 150 fb [13].

In the following I shall consider the possibility that a new resonance around 2 TeV contributes to some of the channels, while others are populated by misidentification of the boson-tagged jet: for instance, one may have a neutral resonance that only couples to the WW and ZZ channels, with the excess in the WZ channel due to contamination. In particular I consider a new weak singlet pseudo-scalar particle $\eta_{\rm WZ}$, coupling to gauge bosons via a Lagrangian term of the type of the Wess-Zumino-Witten (WZW) anomaly [14,15,16], decaying into two weak bosons (WW, ZZ) while being produced via gluon fusion at the LHC. This effective term is theoretically well motivated especially in scenarios of strong dynamics for the electroweak sector, where such states arise as massive scalars associated to an anomalous global symmetry of the dynamics. On phenomenological ground, we allow the couplings to vary in order to explore a large class of models of this type. This exercise will be indeed valuable in general as the coupling via the anomalous WZW term, depending on the quantum numbers of the new fermions in the model is able to populate in different ratios the diboson channels, allowing also to explain excesses at other masses such as the the 750 GeV one (see for example, following the same idea [17]). For a more general discussion of other possibilities see the Les Houches working group reports [18,19].

I shall assume assume that this pseudo-scalar $\eta_{\rm WZ}$ is fermiophobic, i.e., its couplings to the SM fermions, in particular to the top quark, are vanishing or tiny. The coupling to fermions require extra interaction terms which may or may not be present, and their absence is a realistic possibility in composite models, where particles with these properties are typically present [24]. Another interesting point is that new scalar resonances are typically expected to be lighter that their vector counterparts, so it is quite reasonable to discover first such a pseudo–scalar particle at a lower mass than new vectors, as in QCD.

2 An effective model

Before discussing any detailed model building in terms of composite states made of new fermions, it is worth using an effective Lagrangian approach in order to evaluate the size of the parameters needed to obtain a scenario compatible with the diboson excess. As discussed previously I assume that the $\eta_{\rm WZ}$ couples to gluons and the weak bosons, as in the case of the anomaly, and does not couple to the SM quarks and leptons. The excess points to an effective diboson cross section of about 10 fb. This implies that the production cross section $\sigma(gg \to \eta_{\rm WZ})$ should be around 100 fb in order to explain the diboson excesses as the Branching Ratio to the WW channel is roughly ${\rm Br}(\eta_{\rm WZ} \to W^+W^-) \sim 2(N_c\alpha_2)^2/(8\alpha_3^2) \sim 10\%$ for an anomaly induced coupling. For the ZZ mode it is half of it. Thus the desired situation, $\sigma \cdot {\rm Br}(\eta_{\rm WZ} \to W^+W^-/ZZ) \sim 10$ fb, can typically be achieved. In this effective model, the WZ excess is considered contamination from the WW/ZZ signals. The total width should not be so large, which is constrained less than about 100 GeV, due to the size of the one-loop effect.

Another point to be considered are the diphoton resonance searches, because the pseudo-scalar can decay into a pair of photons. This should be avoided when considering the excess at about 2 TeV as there are constraints on it, but may be an interesting feature when considering the 750 GeV excess which is precisely in the di–photon channel [17]. For the high-mass diphoton resonances, the CMS collaborations found the constraint of the production cross section times branching ratio less than 0.3 fb for the 2TeV RS graviton [20]. The ATLAS collaborations also performed a similar analysis and the expected 2σ limit is 0.5 fb [21]. The suggested explanation in terms of a WZW term typically satisfies this constraint, as $\Gamma(\eta_{\rm WZ} \to \gamma\gamma)/\Gamma(\eta_{\rm WZ} \to W^+W^-) \sim \alpha^2/2\alpha_2^2 \simeq 0.03$. The decay channel of $\eta_{\rm WZ} \to Zh$ is also potentially dangerous [22,23], however one can safely assume that the mixing between the singlet and the Higgs doublet is absent here and therefore the possible constraint from final states with Higgses can be avoided.

The action for a weak singlet pseudo-scalar $\eta_{\rm WZ}$ with no hypercharge is given by

$$S_\eta = \int d^4x \frac{1}{2}(\partial_\mu \eta_{\rm WZ} \partial^\mu \eta_{\rm WZ} - M_\eta^2\, \eta_{{\rm WZ}}^2) + \Gamma_{{\rm WZ}W}, \tag{1}$$

where M_η is the mass of the pseudo-scalar singlet and the WZW term contains the effective Lagrangian for the diboson decay, $\Gamma_{{\rm WZ}W} \supset \int d^4x\, \mathcal{L}_{\eta VV}$, with

$$\mathcal{L}_{\eta gg} = \kappa_g^\eta \frac{g_3^2}{32\pi^2} \frac{\eta_{\rm WZ}}{F_\eta} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}, \tag{2}$$

$$\mathcal{L}_{\eta WW} = \kappa_W^\eta \frac{g_2^2}{32\pi^2} \frac{\eta_{\rm WZ}}{F_\eta} \epsilon^{\mu\nu\rho\sigma} W^i_{\mu\nu} W^i_{\rho\sigma}, \tag{3}$$

$$\mathcal{L}_{\eta BB} = \kappa_B^\eta \frac{g_Y^2}{32\pi^2} \frac{\eta_{\rm WZ}}{F_\eta} \epsilon^{\mu\nu\rho\sigma} B_{\mu\nu} B_{\rho\sigma}, \tag{4}$$

where the couplings g_3, g_2 and g_Y are respectively the gauge coupling constants of the strong, weak and hypercharge groups. F_η denotes the decay constant of $\eta_{\rm WZ}$, and the couplings κ_g^η, κ_W^η and κ_B^η are unknown pre-factors in the effective description, but they can be calculated precisely in specific realisations when the content of the loop terms is explicit, as we shall see in the following.

3 A toy Vector-like Model

As a first example let us consider to the couplings κ_g^η, κ_W^η and κ_B^η in terms of a simple hypothesis of a vector-like model allowing to obtain the previous couplings simply "counting" the particles in the anomaly loops, using the charge assignments given in the following table:.

The vector-like weak doublets Q and L come with multiplicity n_Q and n_L, respectively. The vector-like fermion $N_{L,R}$ is a singlet with respect to the weak interactions. The total number of flavours is $N_f = 2N_c n_Q + 2n_L + 1$ where $N_c = 3$ is the number of ordinary QCD colours. Imposing a large number of flavours N_f bring towards a situation in which the gauge theory loses asymptotic freedom. In order to avoid this we ask for a negative coefficient of the β function at one-loop, giving $N_f < 11N/(4T(R))$, where $T(R)$ is the trace normalisation. For the two-index anti-symmetric representation, $T(R) = (N-2)/2$. As an example, the theory with $N = 5$ and $n_Q = n_L = 1$ is asymptotically free. The anomaly type diagram corresponding to the effective vertices of Eq. (4) give the following correspondence

$$\kappa_g^\eta = \frac{1}{2}N(N-1)\cdot 2n_Q, \qquad \kappa_W^\eta = \frac{1}{2}N(N-1)\cdot(N_c n_Q + n_L), \tag{5}$$

with $\kappa_B^\eta = \kappa_{WB}^\eta = 0$, where $N_c = 3$ is the number of colours. For a fundamental representation, the factor $N(N-1)/2$ should be replaced by N. The coefficient κ_γ^η of the WZW term for the

Table 1: Quantum numbers of the vector-like model under the dynamics $SU(N)$, and the SM gauge symmetries. R and L are the chirality of the fermion fields.

	$SU(N)$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$Q_L = (Q_1, Q_2)_L$	$\square$	**3**	**2**	0
$Q_R = (Q_1, Q_2)_R$	$\square$	**3**	**2**	0
$L_L = (L_1, L_2)_L$	$\square$	**1**	**2**	0
$L_R = (L_1, L_2)_R$	$\square$	**1**	**2**	0
N_L	$\square$	**1**	**1**	0
N_R	$\square$	**1**	**1**	0

η_W–γ-γ coupling is calculated from the above ones and gives $\kappa_\gamma^\eta = \kappa_W^\eta$ in this toy model. The number $\kappa_W^\eta/\kappa_g^\eta = 2$ for $n_Q = n_L = 1$ corresponds to the number of the weak doublets over that of the quark flavours and plays an important role in the explanation of the diboson excess. Using the numerical values: $n_Q = 1$, $n_L = 1$, $N = 2$, $N_c = 3$, which translates into $\kappa_g^\eta = 2$ and $\kappa_\gamma^\eta = \kappa_W^\eta = 4$, and $F_\eta = 500$ GeV, the production cross-section of the η_{WZ} particle is 0.615 fb and its total width 1.12 GeV at LHC with 8 TeV of centre of mass energy for $m_{\eta_{\mathrm{WZ}}} = 2$ TeV.

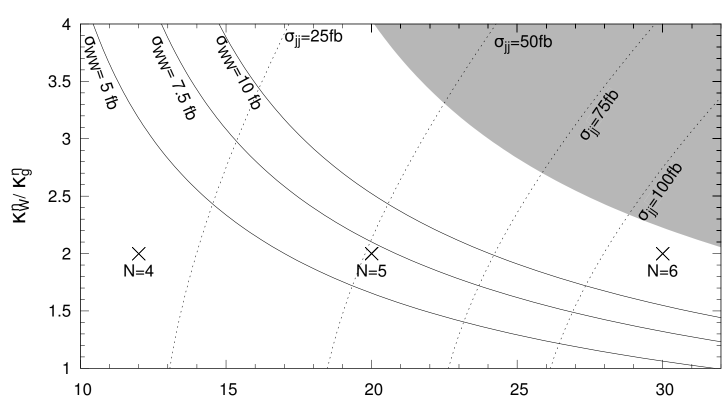

Figure 1 – Cross section times branching ratios on the κ_g^η–$\kappa_W^\eta/\kappa_g^\eta$ plane for $F_\eta = 500$ GeV and $\kappa_B^\eta = 0$. The shaded region in the right upper area is excluded owing to $\sigma(gg \to \eta_{\mathrm{WZ}}) \cdot \mathrm{Br}(\eta_{\mathrm{WZ}} \to \gamma\gamma) > 0.5$fb. The numbers $N = 4, 5, 6$ represent the corresponding values for the vector-like model with $n_Q = n_L = 1$.

Using $N = 5$ and all the other parameters unchanged, increases the couplings by a factor of 10, therefore $\kappa_g^\eta = 20$ and $\kappa_\gamma^\eta = \kappa_W^\eta = 40$, while the production cross-section and width of the η_{WZ} particle are a factor of 100 larger (production cross-section 61.5 fb and total width 112 GeV). The branching fractions are given in Table 2.

These are just indications based on the choice of parameters indicated above. Increasing N (or decreasing F_η) will increase the cross-section and allow reaching a value compatible with the excess.

Table 2: Decay modes and branching fraction of η_{WZ} with mass 2 TeV and $\kappa^{\eta}_{W}/\kappa^{\eta}_{g} = 2$.

decay mode	BR
gg	83.%
WW	11.2%
ZZ	3.2%
$Z\gamma$	2%
$\gamma\gamma$	0.4%

4 A more realistic model

The previous section introduced a simple vector-like model allowing to test the idea of a scalar coupling to the gauge boson via the WZW term at the effective level or the triangle type vertex at one–loop order in the more fundamental description in terms of fermionic states giving rise to bound states in a strong type electroweak model. The previous example completely disregarded many important points which should be analyses in a more complete setup. A more realistic example of a composite Higgs model is considered in the following and it is based on the model first introduced in [26] and further discussed in [27]. The discussion in this section is based on the detailed analysis for the diboson excess performed in [28]. The model is based on a confining gauge theory with four fermions Q and six fermions χ. The Q fermions provide an $SU(4)$ flavour symmetry which is spontaneously broken into $Sp(4)$ to give a composite Higgs and two SM singlets as pNGBs. The χ fermions in a **6** of $SU(6)$, spontaneously or explicitly broken into $SO(6)$. This allows to obtain coloured fermionic bound states which are the top partners usually introduced in the effective Lagrangian descriptions for the composite Higgs models.

Table 3: Fermionic fields and transformation under the gauged symmetry group $\mathrm{Sp}(2N_c)\times\mathrm{SU}(3)_c\times$ $\mathrm{SU}(2)_L\times$ $\mathrm{U}(1)_Y$, and under the global symmetries $\mathrm{SU}(4)\times\mathrm{SU}(6)\times\mathrm{U}(1)$.

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	SU(4)	SU(6)	U(1)
Q_1 Q_2	$\square$	$\mathbf{1}$	$\mathbf{2}$	0	$\mathbf{4}$	$\mathbf{1}$	q_Q
Q_3	$\square$	$\mathbf{1}$	$\mathbf{1}$	1/2			
Q_4	$\square$	$\mathbf{1}$	$\mathbf{1}$	−1/2			
χ_1 χ_2 χ_3	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{3}$	$\mathbf{1}$	2/3	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4 χ_5 χ_6	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	−2/3			

The QQ and $\chi\chi$ mesons, each contain one $Sp(4) \times SO(6)$ singlet, σ_Q and σ_χ, which are associated to the spontaneously broken $U(1)_Q$ and $U(1)_\chi$. One linear combination of these is $Sp(2N_c)$ anomaly free, leaving only one pNGB from this sector. The other one is expected to obtain a large mass from $Sp(2N_c)$ instanton effects. In addition, QQ contains a boson multiplet in the $(5, 1)$ under $Sp(4) \times SO(6)$. In terms of the $SU(2)_L \times SU(2)_R \subset Sp(4)$, it decomposes into (H, η) in $(2, 2) \oplus (1, 1)$, and the bidoublet is identified with the SM-like Higgs while η is another SM singlet pNGB.

The anomaly coupling coefficients κ^i_G are given in table 4.

Table 4: Anomaly coefficients of σ_Q, σ_χ, and η.

	σ_Q	σ_χ	η
κ_g	0	$(2N_c+1)(N_c-1)$	0
κ_W	$2N_c$	0	$2N_c \frac{\cos(v/f)}{2\sqrt{2}}$
κ_B	$2N_c$	$\frac{8}{3}(2N_c+1)(N_c-1)$	$-2N_c \frac{\cos(v/f)}{2\sqrt{2}}$

The $Sp(2N_c)$ anomaly breaks $U(1)_Q \times U(1)_\chi \to U(1)_\sigma$. The Goldstone Lagrangian of σ_Q and σ_χ is:

$$\mathcal{L}_{\text{kin,GB}} = \frac{f_Q^2}{2} \partial_\mu \Sigma_{QQ}^\dagger \partial^\mu \Sigma_{QQ} + \frac{f_\chi^2}{2} \partial_\mu \Sigma_{\chi\chi}^\dagger \partial^\mu \Sigma_{\chi\chi}, \tag{6}$$

where

$$\Sigma_{QQ} = e^{i\sigma_Q/f_Q}, \quad \Sigma_{\chi\chi} = e^{i\sigma_\chi/f_\chi}. \tag{7}$$

The conserved current (up to the anomaly) of a $U(1)$ transformation $\Sigma_{QQ} \to e^{2q_Q\alpha}\Sigma_{QQ}, \Sigma_{\chi\chi} \to e^{2q_\chi\alpha}\Sigma_{\chi\chi}$ is $j^\mu \propto \partial^\mu \left(f_Q q_Q \sigma_Q + f_\chi q_\chi \sigma_\chi\right)$, such that the canonically normalised pNGB corresponding to this $U(1)$ and its orthogonal combination are

$$\sigma = \cos\phi \sigma_Q + \sin\phi \sigma_\chi \tag{8}$$
$$\sigma' = -\sin\phi \sigma_Q + \cos\phi \sigma_\chi \tag{9}$$

with $\tan\phi = f_\chi q_\chi / f_Q q_Q$.
The composite particle labelled σ is $Sp(2N_c)$ anomaly-free when $q_Q = -3(N_c-1)q_\chi$ and thus remains a pNGB. The one labelled σ' obtains a mass from the anomaly and from $Sp(2N_c)$ instanton effects. In this model the η particle does not couple to gluons and therefore is not a good candidate for the excess (too small production cross section). σ can be made massive by explicit breaking of $U(1)_\sigma$ and can be produced from gluon fusion and has decay channels into WW and ZZ. σ' is massive even without an explicit breaking term, and it has the required couplings. Both σ and σ' should be therefore analysed in more detail.

The coefficients κ^σ/f_σ give branching ratios (normalised to the one of $\Gamma_{\sigma\to WW}$) of the σ particle in the range (see [28] for more details):

$$\frac{\Gamma_{\sigma\to gg}}{\Gamma_{\sigma\to WW}} = 5.1 \leftrightarrow 3.3, \tag{10}$$
$$\frac{\Gamma_{\sigma\to ZZ}}{\Gamma_{\sigma\to WW}} = 0.29 \leftrightarrow 0.31, \tag{11}$$
$$\frac{\Gamma_{\sigma\to Z\gamma}}{\Gamma_{\sigma\to WW}} = 0.19 \leftrightarrow 0.17, \tag{12}$$
$$\frac{\Gamma_{\sigma\to \gamma\gamma}}{\Gamma_{\sigma\to WW}} = 0.021 \leftrightarrow 0.033, \tag{13}$$

where the first number is for $N_c = 2$ while the second one is obtained in the large N_c limit (with $g_3 = 1.033$, $g_2 = 0.628$, and $\sin^2_W = 0.2319$) at 2 TeV.

The production cross section of a scalar resonance at LHC Run 1 is given by:

$$\sigma_{R1}(gg\to\sigma) = \left(\frac{\kappa_g^\sigma}{2}\right)^2 \frac{(1\text{TeV})^2}{f_\sigma^2}\, 0.615\,\text{fb} \tag{14}$$

while at LHC Run 2 is:

$$\sigma_{R2}(gg\to\sigma) = \left(\frac{\kappa_g^\sigma}{2}\right)^2 \frac{(1\text{TeV})^2}{f_\sigma^2}\, 8.11\,\text{fb}. \tag{15}$$

After checking the bounds on branching fractions, one needs to consider whether the model can provide a large enough cross section for the diboson excess. From Eqs. (14) and (15), one can see that the production cross section can be raised by either increasing κ_g^σ (which means increasing N_c) or by decreasing f_σ. The branching ratios are independent of f_σ and only mildly depend on N_c. It turns out that the cross section can be around 10 fb using a low value of f_Q and/or a high value of N_c. Note that $N_c \leq 36$ is required in order to maintain asymptotic freedom, which implies roughly an upper bound $f_Q < 1.6$ TeV if σ is considered the source of the 2 TeV diboson anomaly.

5 Conclusions

I have discussed the idea that excesses in diboson channels with no or little fermion counterpart in the final state, such as those present in Run 1 data at 2 TeV, can be explained in a simple way in composite models which typically contain a pseudo Nambu-Goldstone boson with anomalous couplings to gluons and electroweak gauge bosons. In the effective Lagrangian description the WZW terms have arbitrary coefficients, but when considering an underlying dynamical model, these can be calculated bringing precise numbers to be confronted with data. The branching ratios obtained in these models allow to explain a diboson excess in the hadronic WW and ZZ channel without contradiction with the present bounds. As soon as the situation concerning the diboson excesses will be clarified by the new Run 2 analyses, it will be possible to either pinpoint a particular set of effective couplings (therefore selecting particular models in terms of constituent fermions and dynamics) or obtain more stringent bounds.

Acknowledgments

I would like to thank all the people who participated in the present work and in the many discussions we had together on this and related subjects: H.Cai, G.Cacciapaglia, T.Flacke, M.Hashimoto, S.J.Lee, M.Lespinasse, Y.Okada, A.Parolini, F.Sannino. The caricature on the front page is courtesy of E.D. I wish to thank the France-Japan Particle Physics Lab (TYL/FJPPL) as well as the DéfiInphyNiTi - projet structurant TLF; the Labex-LIO (Lyon Institute of Origins) under grant ANR-10-LABX-66 and FRAMA (FR3127, Fédération de Recherche "André Marie Ampère") for partial support.

References

1. G. Cacciapaglia, A. Deandrea and M. Hashimoto, "Scalar Hint from the Diboson Excess?," Phys. Rev. Lett. **115** (2015) no.17, 171802.
2. G. Aad *et al.* [ATLAS Collaboration], "Search for high-mass diboson resonances with boson-tagged jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," arXiv:1506.00962 [hep-ex].
3. V. Khachatryan *et al.* [CMS Collaboration], "Search for massive resonances in dijet systems containing jets tagged as W or Z boson decays in pp collisions at $\sqrt{s} = 8$ TeV," JHEP **1408**, 173 (2014).
4. G. Aad *et al.* [ATLAS Collaboration], "Search for production of WW/WZ resonances decaying to a lepton, neutrino and jets in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," Eur. Phys. J. C **75**, no. 5, 209 (2015).
5. V. Khachatryan *et al.* [CMS Collaboration], "Search for massive resonances decaying into pairs of boosted bosons in semi-leptonic final states at $\sqrt{s} = 8$ TeV," JHEP **1408**, 174 (2014).
6. G. Aad *et al.* [ATLAS Collaboration], "Search for WZ resonances in the fully leptonic channel using pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," Phys. Lett. B **737**, 223 (2014).

7. V. Khachatryan *et al.* [CMS Collaboration], "Search for new resonances decaying via WZ to leptons in proton-proton collisions at $\sqrt{s} = 8$ TeV," Phys. Lett. B **740**, 83 (2015).
8. The ATLAS collaboration, "Search for diboson resonances in the $\nu\nu qq$ final state in pp collisions at $\sqrt{s}$ =13 TeV with the ATLAS detector," ATLAS-CONF-2015-068.
9. The ATLAS collaboration, "Search for diboson resonances in the llqq final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," ATLAS-CONF-2015-071.
10. The ATLAS collaboration, "Search for resonances with boson-tagged jets in 3.2 fb1 of p p collisions at s = 13 TeV collected with the ATLAS detector," ATLAS-CONF-2015-073.
11. The ATLAS collaboration, "Search for WW/WZ resonance production in the $\ell\nu qq$ final state at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC," ATLAS-CONF-2015-075.
12. CMS Collaboration [CMS Collaboration], "Search for massive resonances decaying into pairs of boosted W and Z bosons at $\sqrt{s} = 13$ TeV," CMS-PAS-EXO-15-002.
13. G. Aad *et al.* [ATLAS Collaboration], "Search for new phenomena in dijet mass and angular distributions from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," Phys. Lett. B **754** (2016) 302.
14. J. Wess and B. Zumino, "Consequences of anomalous Ward identities," Phys. Lett. B **37**, 95 (1971).
15. E. Witten, "Global Aspects of Current Algebra," Nucl. Phys. B **223**, 422 (1983).
16. T. Fujiwara, T. Kugo, H. Terao, S. Uehara and K. Yamawaki, "Nonabelian Anomaly and Vector Mesons as Dynamical Gauge Bosons of Hidden Local Symmetries," Prog. Theor. Phys. **73**, 926 (1985); M. Hashimoto, "Isospin breaking effects in the anomalous processes with vector mesons," Phys. Lett. B **381**, 465 (1996);
17. A. Belyaev, G. Cacciapaglia, H. Cai, T. Flacke, A. Parolini and H. Serodio, "Singlets in Composite Higgs Models in light of the LHC di-photon searches," arXiv:1512.07242 [hep-ph].
18. J. Brehmer *et al.*, "The Diboson Excess: Experimental Situation and Classification of Explanations; A Les Houches Pre-Proceeding," arXiv:1512.04357 [hep-ph].
19. G. Brooijmans *et al.*, "Les Houches 2015: Physics at TeV colliders - new physics working group report," arXiv:1605.02684 [hep-ph].
20. CMS Collaboration [CMS Collaboration], "Search for High-Mass Diphoton Resonances in pp Collisions at sqrt(s)=8 TeV with the CMS Detector," CMS-PAS-EXO-12-045.
21. G. Aad *et al.* [ATLAS Collaboration], "Search for high-mass diphoton resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," arXiv:1504.05511 [hep-ex].
22. G. Aad *et al.* [ATLAS Collaboration], "Search for a new resonance decaying to a W or Z boson and a Higgs boson in the $\ell\ell/\ell\nu/\nu\nu + b\bar{b}$ final states with the ATLAS Detector," Eur. Phys. J. C **75**, no. 6, 263 (2015).
23. V. Khachatryan *et al.* [CMS Collaboration], "Search for a massive resonance decaying into a Higgs boson and a W or Z boson in hadronic final states in proton-proton collisions at sqrt(s) = 8 TeV," arXiv:1506.01443 [hep-ex].
24. A. Arbey, G. Cacciapaglia, H. Cai, A. Deandrea, S. Le Corre and F. Sannino, "Fundamental Composite Electroweak Dynamics: Status at the LHC," arXiv:1502.04718 [hep-ph].
25. M. E. Peskin and T. Takeuchi, "A New constraint on a strongly interacting Higgs sector," Phys. Rev. Lett. **65**, 964 (1990); "Estimation of oblique electroweak corrections," Phys. Rev. D **46**, 381 (1992).
26. J. Barnard, T. Gherghetta and T. S. Ray, "UV descriptions of composite Higgs models without elementary scalars," JHEP **1402** (2014) 002.
27. G. Cacciapaglia, H. Cai, A. Deandrea, T. Flacke, S. J. Lee and A. Parolini, "Composite scalars at the LHC: the Higgs, the Sextet and the Octet," JHEP **1511** (2015) 201.
28. H. Cai, T. Flacke and M. Lespinasse, "A composite scalar hint from di-boson resonances?," arXiv:1512.04508 [hep-ph].