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Heavy vector partners of the light composite Higgs

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ABSTRACT

If the Higgs boson $H(125)$ is a composite due to new strong interactions at high energy, it has spin-one partners, ρ_H and a_H, analogous to the ρ and a_1 mesons of QCD. These bosons are heavy, their mass determined by the strong interaction scale. The strongly interacting particles light enough for ρ_H and a_H to decay to are the longitudinal weak bosons $V_L = W_L, Z_L$ and the Higgs boson H. These decay signatures are consistent with resonant diboson excesses recently reported near 2 TeV by ATLAS and CMS. We calculate $\sigma \times BR(\rho_H \to VV) =$ few fb and $\sigma \times BR(a_H \to VH) = 0.5$–1 fb at $\sqrt{s} = 8$ TeV, increasing by a factor of 5–7 at 13 TeV. Other tests of the hypothesis of the strong-interaction nature of the diboson resonances are suggested.

1. Introduction

The ATLAS and CMS Collaborations have reported 2–3σ excesses in the 8-TeV data of high-mass diboson ($VV = WW, WZ, ZZ$) production [1–3]. The ATLAS excesses are in nonleptonic data (both $V \to \bar{q}q$ jets) in which the boosted V-jet is called a W (Z) if its mass M_V is within 13 GeV of 82.4 (92.8) GeV. They appear in all three invariant-mass "pots", M_{WW}, M_{WZ} and M_{ZZ}, although there may be as much as 30% spillover between neighboring pots. Perhaps not surprisingly, the largest excess is in M_{WZ}. It is centered at 2 TeV, with a 3.4σ local, 2.5σ global significance. The ATLAS nonleptonic WZ excess has been estimated to correspond to a signal cross section times branching ratio of $\mathcal{O}(10\text{ fb})$.[1] The CMS papers report semileptonic ($V \to \ell\nu$ or $\ell^+\ell^-$ plus $V \to \bar{q}q$) as well as nonleptonic VV events. In the purely nonleptonic sample, a boosted jet is called a W or Z candidate if $70 < M_V < 100$ GeV. A nonleptonic V-jet in the semileptonic sample is considered a W-jet candidate if $65 < M_V < 105$ GeV and a Z-candidate if $70 < M_V < 110$ GeV.[2] The semileptonic data is divided into WW and ZZ pots. There is a 1σ excess in WW and 2σ in ZZ, both centered at 1.8 TeV. CMS combined its semileptonic and nonleptonic data (which also showed 1–2σ excesses near 1.8 TeV), and still obtained a 2σ effect at 1.8 TeV. ATLAS saw no similar excesses in its semileptonic VV-data [4,5]. Both experiments also looked for VH resonances. CMS reported a 2σ excess near 1.8 TeV in $WH \to \ell\nu\bar{b}b$ [6]. ATLAS searched for WH and ZH in semileptonic modes but saw no excess [7].

Despite the low statistics, 5–10 events, of the ATLAS and CMS excesses, their number and proximity have inspired a number of theoretical papers variously proposing them to be due to production of heavy weak W' and Z' bosons [8–11], of heavy vector bosons associated with new strong dynamics at the TeV scale that is responsible for electroweak symmetry breaking [12–14], or of a new heavy scalar [15,16].

If these excesses are confirmed in Run 2 data — and that's a big if! — their most plausible explanation, in our opinion, is that they are the lightest vector and, possibly, axial-vector triplet bound states of new strong interactions responsible for the compositeness of the 125 GeV Higgs boson H. If the Higgs is composite, it is widely believed to be built of fermion-(anti)fermion pairs which carry weak isospin and whose other bound states respect custodial $SU(2)$ symmetry (see, e.g., Refs. [17–20]). Then there are isovector and isoscalar bosons analogous to the familiar ρ, ω and a_1 mesons. In this paper we concentrate on the isovectors, which we call ρ_H and a_H to emphasize their relation to H. We shall explain that the only hadrons of the new interaction lighter than ρ_H and a_H are the longitudinally-polarized weak bosons, $V_L = W_L, Z_L$, and H itself,

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[1] G. Brooijmans, communication.

[2] This discussion does not do justice to the selections of W and Z jets. The reader is urged to consult the ATLAS and CMS papers for a complete description of nonleptonic W, Z-jet identification.

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which, therefore, are their decay products. The production mechanisms of ρ_H and a_H are the Drell–Yan (DY) process, induced by mixing with the photon, W and Z, and weak vector boson fusion (VBF). We find total production times decay rates of a few femtobarns (fb), dominated by DY. The hallmark of the isovectors' underlying strong dynamics are their large widths, dominated by decays involving V_L. The diboson data favors $\Gamma(\rho_H) \lesssim 200$ GeV, though a somewhat greater width is still allowed. The mode $\rho_H \to V_L V_L$ is completely dominant. The main two-body decay mode of a_H is $V_L H$, while the longitudinal-transverse mode, $V_L V_T$, and the on-mass-shell $\rho_H V_L$ mode are much suppressed. We have not estimated the nonresonant three-body mode $a_H \to 3V_L$.

Isovectors of composite Higgs dynamics and their interactions with Standard Model (SM) particles, including the Higgs, have been anticipated in several recent papers [17–20]. The models in Refs. [17–19] and the particular model we use for describing isovector couplings to SM particles are conveniently described by a hidden local symmetry (HLS) [21] — $SU(2)_L \otimes SU(2)_R$ with equal gauge couplings, $g_L = g_R$. This parity is softly (spontaneously) broken. The resulting vector and axial-vector bosons comprise two isotriplets, nearly degenerate within each multiplet. Their dimension-three and four interactions, including those with electroweak (EW) gauge bosons respect this parity up to corrections of order the EW gauge couplings.

In light composite Higgs models in which H is a pseudo-Goldstone boson (PGB) (see, e.g., Refs. [22,23] for a review) the isovectors' expected mass is $\sim g_{\rho_H} f$, where $g_{\rho_H} \simeq g_L = g_R$ and f is the PGB decay constant, typically $\mathcal{O}(1\text{ TeV})$. In the model of Ref. [20], electroweak symmetry breaking is driven *not* by technicolor, but by strong extended technicolor interactions (ETC) at a scale of 100's of TeV. The Higgs boson in this Nambu–Jona-Lasinio-like model [24,25] is not a PGB; it is made light by fine-tuning the strength of the ETC interaction coupling to be near the critical value for spontaneous electroweak symmetry breaking. But ETC's unbroken subgroup, technicolor, is a confining interaction and it binds technifermions into hadrons whose typical mass is the technicolor scale $\Lambda_{TC} = \mathcal{O}(1\text{ TeV})$. We can also use the HLS formalism to describe the ρ_H, a_H in this scenario and so, again, their masses can be expressed as $g_{\rho_H} f$ where $f \simeq \Lambda_{TC}$. From the earliest days of technicolor, the mass of the technirho in a one-doublet model was estimated (naively) to be ~ 1.8 TeV [26,27].

The interactions of the isovectors with W, Z and H are given in Sec. 2. These are used to calculate the isovectors' decay rates and production cross sections in Sec. 3. Finally, in Sec. 4 we make comments and predictions that should test our composite-Higgs hypothesis in the first year or two of LHC Run 2.

2. ρ_H, a_H couplings to Standard Model particles

In a light composite Higgs model the strongly-interacting bound states lighter than ρ_H are the quartet consisting of three Goldstone bosons, $W_L^\pm$ and Z_L, and the scalar H. But is that all? If the model has other PGBs they may be lighter than ρ_H. But then we would have to infer that the ρ_H production rate is rather larger than a few fb to make up for the smaller VV branching ratio and that, we shall see in Sec. 3, is difficult to accommodate in this sort of model. In the model of Ref. [20] the low-energy theory below M_{ρ_H} *is* the SM plus suppressed higher-dimension operators. Just above the electroweak symmetry breaking transition, $W_L^\pm$, Z_L, H are a light degenerate quartet; just below it, they are three Goldstone bosons and a light scalar. There are no other light hadrons of the strong interactions than these four. They and, presumably, ρ_H are lighter than a_H. To minimize the contribution to the S-parameter [28–32] from the low-lying hadrons, we assume that a_H and ρ_H are nearly degenerate with the same coupling strength to the electroweak currents (see, e.g., Refs. [33,34]). This greatly suppresses the strong decay $a_H \to \rho_H V_L$.

The effective Lagrangian describing $\rho_H VV$ and $a_H VV$ couplings is obtained from the HLS approach describing the isovectors as $SU(2)_L \otimes SU(2)_R$ gauge bosons. Refs. [18,19] give quite similar results for these couplings. We use ones like these that are given in Sec. VI of Ref. [34], adapted to the case of a single technidoublet with no light PGBs, and with couplings chosen to cancel the ρ_H and a_H contributions to S. They are:

$$\mathcal{L}(\rho_H \to VV) = -\frac{ig^2 g_{\rho_H} v^2}{2M_{\rho_H}^2}\rho^0_{H\mu\nu} W^+_\mu W^-_\nu - \frac{ig^2 g_{\rho_H} v^2}{2M_{\rho_H}^2 \cos\theta_W}\left(\rho^+_{H\mu\nu} W^-_\mu - \rho^-_{H\mu\nu} W^+_\mu\right) Z_\nu\,, \quad (1)$$

$$\mathcal{L}(a_H \to VV) = \frac{ig^2 g_{\rho_H} v^2}{2M_{\rho_H}^2} a^0_{H\mu}\left(W^+_{\mu\nu} W^-_\nu - W^-_{\mu\nu} W^+_\nu\right) - \frac{ig^2 g_{\rho_H} v^2}{2M_{\rho_H}^2 \cos\theta_W}\left[a^+_{H\mu}\left(W^-_\nu Z_{\mu\nu} - W^-_{\mu\nu} Z_\nu\right) - \text{h.c.}\right]. \quad (2)$$

Note the isospin symmetry of these couplings. Here, $G_{\mu\nu} = \partial_\mu G_\nu - \partial_\nu G_\mu$, g is the weak-$SU(2)$ coupling; g_{ρ_H} is the left–right symmetric HLS gauge coupling for the isovectors. The ρ_H mass in Ref. [34] is nominally given by $M_{\rho_H} = \frac{1}{2} g_{\rho_H} f_{\rho_H}$, where f_{ρ_H} is the HLS decay constant (analogous to the decay constant of a PGB composite Higgs). If we take $f_{\rho_H} = 1\text{ TeV} \simeq 4v$, where $v = 246$ GeV is the Higgs vacuum expectation value, then $g_{\rho_H} = 4$ for $M_{\rho_H} = 2$ TeV.

For highly-boosted weak bosons, as is the case here, $V^{\pm,0}_{L\mu} = \partial_\mu \pi^{\pm,0}/M_V + \mathcal{O}(M_V/E_V)$, where π is the pseudoscalar Goldstone boson eaten by V. Then, the $V_L V_L$ part of $V_{\mu\nu}$ is suppressed by M_V^2/E_V^2 and, while $\rho_H \to V_L V_L$ is allowed, only the strongly suppressed $a_H \to V_L V_T$ is. The same parity argument applies in reverse to the decays $\rho_H, a_H \to V_L H$. Furthermore, for (nearly) degenerate ρ_H and a_H, the two comprise parity-doubled triplets and, for a *light* Higgs, the decay rates $\rho_H \to V_L V_L$ and $a_H \to V_L H$ are identical.[3] Thus,

$$\mathcal{L}(a_H \to VH) = g g_{\rho_H} v\left(a^+_{H\mu} W^-_\mu + a^-_{H\mu} W^+_\mu\right) H + \frac{g g_{\rho_H} v}{\cos\theta_W} a^0_{H\mu} Z_\mu H\,. \quad (3)$$

The $a_H \rho_H V$ couplings are also taken from Ref. [34]:

$$\mathcal{L}(a_H \to \rho_H V) = -\frac{igg^2_{\rho_H} v^2}{2\sqrt{2}M^2_{\rho_H}}\left[a^0_{H\mu}\left(\rho^+_{H\mu\nu} W^-_\nu - \rho^-_{H\mu\nu} W^+_\nu\right) + a^+_{H\mu}\left(\rho^-_{H\mu\nu} Z_\nu/\cos\theta_W - \rho^0_{H\mu\nu} W^-_\nu\right) - \text{h.c.}\right]. \quad (4)$$

Finally, the amplitudes for DY production of ρ_H, a_H and their decay to VV, VH involve their mixing with γ, W, Z. (The ρ_H and a_H have no appreciable direct coupling to SM fermions in the composite Higgs models considered here.) The mixing is of $\mathcal{O}(gM^2_{\rho_h}/g_{\rho_H}, g' M^2_{\rho_h}/g_{\rho_H})$ and the amplitudes also depend on the electroweak quantum numbers of the constituent fermions of ρ_H, a_H. We use the couplings of Ref. [35], appropriate to a single fermion doublet, for which we assume electric charges $\pm\frac{1}{2}$. The

[3] More precisely, they are identical in the Wigner–Weyl mode of electroweak symmetry in which $(H, \boldsymbol{\pi})$ are a degenerate quartet. We thank T. Appelquist for this simple argument for the $a_H VH$ coupling strength.

DY cross sections given in Ref. [35] are easily modified for the case at hand in which there are no other light PGBs. They are encoded in Pythia 6.4 [36].

3. ρ_H, a_H decay rates and cross sections

The ρ_H decay rates are completely dominated by the emission of a pair of longitudinally-polarized weak bosons. The factor of $M^2_{\rho_H}$ from the longitudinal polarization vectors is canceled by the $1/M^2_{\rho_H}$ in Eq. (1), giving (for $M_{\rho_H} \gg M_W$)

$$\Gamma(\rho^0_H \to W^+W^-) \cong \Gamma(\rho^\pm_H \to W^\pm Z) \cong \frac{g^2_{\rho_H} M_{\rho_H}}{48\pi}\,. \tag{5}$$

The $a_H \to VH$ decay rate from Eq. (3) is

$$\Gamma(a^0 \to ZH) \cong \Gamma(a^\pm \to W^\pm H) \cong \frac{g^2_{\rho_H} M_{a_H}}{48\pi}\,. \tag{6}$$

As noted above, CMS, but not ATLAS, saw a 2σ excess in the WH channel. If this excess persists and is confirmed by ATLAS, in our model it must be due to a_H.

The greatly suppressed decay rate of a_H to a pair of weak bosons is

$$\Gamma(a^0_H \to W^+W^-) \cong \Gamma(a^\pm_H \to W^\pm Z) \cong \frac{g^2_{\rho_H} M^2_W M^3_{a_H}}{24\pi M^4_{\rho_H}}\,. \tag{7}$$

Finally, the decay rate for a_H to individual $\rho_H V$ states is

$$\Gamma(a_H \to \rho_H V) = \frac{g^2}{192\pi}\left(\frac{g_{\rho_H} v}{M_{\rho_H}}\right)^4 \frac{p^3}{(M_{a_H} M_{\rho_H} M_W)^2} \times \left[6M^2_{\rho_H}(M^2_{a_H} + M^2_V) + M^4_{\rho_H} + M^2_{a_H} p^2 - (M^2_{a_H} - M^2_V)^2\right], \tag{8}$$

where p is the $V = W, Z$ momentum in the a_H rest frame. An interesting possibility would be that this quasi-two-body decay is not very limited by phase space. The two weak bosons from ρ_H would have $M_{VV} \simeq M_{\rho_H}$ and the third V would be soft and not included in the diboson mass. A possibility like this was considered in Ref. [37]. Unfortunately, the $a_H \to \rho_H V$ decay rate is only a few MeV in our model.

The decay rates are listed in Table 1 for $M_{\rho_H} = 1800, 1900, 2000$ GeV and $M_{a_H} = 1.05 M_{\rho_H}$; the strong coupling is fixed at $g_{\rho_H} = 1900$ GeV$/2v = 3.862$. The ~ 200 GeV width of ρ_H is compatible with the existing data.

The main production mechanisms of the isovectors are DY and VBF. The cross sections for the dominant modes, $\rho^{\pm,0}_H \to W^\pm Z$, W^+W^- and $a^{\pm,0}_H \to W^\pm H$, ZH, are listed in Table 2 for $M_{\rho_H} =$ 1800–2000 GeV, $M_{a_H} = 1.05 M_{\rho_H}$ and $g_{\rho_H} = 3.862$. The DY and VBF rates for ρ_H are given separately; VBF rates for a_H are very small. No K-factor has been applied to the cross sections. The rates reveal the following (all $BR \simeq 1$)

- $\sigma_{DY}(a_H) \simeq 0.5\,\sigma_{DY}(\rho_H)$.
- $\sigma_{DY}(13\text{ TeV}) = 5\text{–}7\,\sigma_{DY}(8\text{ TeV})$.
- $\sigma_{VBF}(a_H) \lesssim 0.01\,\sigma_{VBF}(\rho_H)$.
- $\sigma_{VBF}(\rho_H) \simeq \frac{1}{4}\sigma_{DY}(\rho_H)$ at $\sqrt{s} = 8$ TeV, rising to about $\frac{1}{2}\sigma_{DY}(\rho_H)$ at 13 TeV.
- $\sigma(\rho^\pm_H) \simeq 2\sigma(\rho^0)$ *uniformly*. This is strongly dominated by ρ^+ over ρ^- for DY and VBF and is a consequence of the proton PDFs.

Table 1
Principal decay rates of the isovector bosons ρ_H and a_H for $g_{\rho_H} = 3.862$ and $M_{a_H} = 1.05 M_{\rho_H}$.

M_{ρ_H} (GeV)	$\Gamma(\rho_H \to VV)$ (GeV)	$\Gamma(a_H \to VH)$ (GeV)	$\Gamma(a_H \to VV)$ (GeV)
1800	178	184	0.82
1900	188	196	0.78
2000	198	208	0.74

Table 2
Production cross sections at the LHC of the isovector bosons ρ_H and a_H for $g_{\rho_H} = 3.862$ and $M_{a_H} = 1.05 M_{\rho_H}$ ($\rho^\pm_H = \rho^+_H + \rho^-_H$). The individual DY + VBF contributions are given for ρ_H; the VBF rates for a_H are very small and not given. As explained in the text, $g_{\rho_H} = 2.73$ gives 75% larger cross sections and widths half as large for $\rho_H \to VV$. No K-factor has been applied.

$\sqrt{s}$	M_{ρ_H} (GeV)	$\sigma(\rho^\pm_H)_{DY+VBF}$ (fb)	$\sigma(\rho^0_H)_{DY+VBF}$ (fb)	$\sigma(a^\pm_H)$ (fb)	$\sigma(a^0_H)$ (fb)
8	1800	1.53 + 0.36	0.74 + 0.18	0.71	0.37
8	1900	1.05 + 0.24	0.50 + 0.12	0.51	0.27
8	2000	0.73 + 0.15	0.36 + 0.075	0.36	0.17
13	1800	7.61 + 3.67	3.74 + 1.93	4.65	2.23
13	1900	5.74 + 2.62	2.81 + 1.37	3.16	1.69
13	2000	4.37 + 1.90	2.16 + 0.99	2.39	1.27

The DY cross sections vary roughly as $1/g^2_{\rho_H}$ for M_{ρ_H} fixed near 2 TeV. On the other hand, the VBF rate for $\rho_H \to VV$ varies as $g^2_{\rho_H}$ for fixed M_{ρ_H}. Then, e.g., $g_{\rho_H} = 2.73$ gives a 50% larger production rate for $\rho_H \to VV$ and a width half as large.

4. Comments and predictions

In this paper we proposed that the excess diboson events near $M_{VV} = 2$ TeV reported by ATLAS and CMS are due to production of isovector bosons, ρ_H and a_H, associated with new strong dynamics that make the Higgs boson a light composite state. We focused on two types of models that have a custodial $SU(2)$-isospin symmetry and approximate left–right symmetry. We believe our results are equally applicable to both types. Here we make some comments and predictions implied by them and which can be tested in the next couple of years.

1) The $\rho^0_H, a^0_H \to ZZ$ decays are isospin-violating and their rates are very small. Therefore, the ZZ signals claimed by ATLAS and CMS will be understood to have one or two misidentified Z-bosons. (A possibility we have not considered is the production of an $I = 0$ scalar, f_0-like, which could decay to ZZ. Its production would have to be via VBF or, if its constituents are colored, gluon fusion.)
2) It is difficult for us to explain cross sections greater than a few fb for individual diboson (WW or WZ) production at $\sqrt{s} = 8$ TeV. Therefore, we expect that, should these signals be confirmed in Run 2, they will be seen to have been upfluctuations in Run 1, something quite familiar in the history of particle physics, including the discovery of the Higgs boson [38,39].
3) There must be semileptonic VV events, their present spotty evidence being a consequence of low statistics. The $\ell\nu\bar{q}q$ events should have $\sigma(\ell^+)/\sigma(\ell^-) \simeq 2$.
4) The ρ_H width is almost entirely due to strong-interaction decays to VV and is ~ 200 GeV with our parameters. Presumably, it would be best measured in semileptonic VV events.
5) $\rho_H \to VV$ decays involve a pair of longitudinally-polarized weak bosons. Note that boosted V_L tend to produce quark-subjets that have more equal momenta along the parent V-direction than do boosted V_T. Also see Ref. [40].

6) A measurement of the ρ_H width determines whether it is a composite of strong dynamics or a weakly-coupled gauge boson.
7) The *VH* signal should strengthen with more data. It is entirely due to the strong decay $a_H \to VH$, hence it involves V_L and a large width. In our model $\Gamma(a_H) \cong \Gamma(\rho_H)$.
8) There should be forward jets from VBF in $\rho_H \to VV$, but not in $a_H \to VH$.
9) Finally, if H is a PGB, there likely are top and W-partners that keep it light. They are not hadrons of the new strong dynamics and, so, are surely lighter than ρ_H, a_H. They should show up soon. There are *no* top and W-partners needed in the strong-ETC model and there aren't any.

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