Benchmarks for new strong interactions at the LHC

J. Hirn¹, A. Martin¹ and V. Sanz²

¹Department of Physics, Yale University, New Haven CT 06520
²Department of Physics, Boston University, Boston MA 02215

New strong interactions at the LHC may exhibit a richer structure than expected from simply rescaling QCD to the electroweak scale. In fact, a departure from rescaled QCD is required for compatibility with electroweak constraints. To navigate the space of possible scenarios, we use a simple framework, based on a 5D model with modifications of AdS geometry in the infrared. In the parameter space, we select two points with particularly interesting phenomenology. For these benchmark points, we explore the discovery of triplets of vector and axial resonances at the LHC.

Introduction: The two main experimental collaborations at LHC - ATLAS and CMS - classify models of electroweak symmetry breaking (EWSB) in two groups: Supersymmetry (SUSY) or Exotics. The two groups are on a different footing, though: detailed studies of SUSY phenomenology abound, whereas the collider phenomenology of most models referred to as Exotics is still in its infancy, due mostly to the intricacies in handling strong coupling⁴.

The profusion of phenomenological studies of SUSY was spurred by the successes of the Minimal Supersymmetric Standard Model (MSSM) [2], and the parametrical simplicity of minimal Supergravity (mSUGRA). mSUGRA-MSSM provided a compact, manageable framework appropriate for collider studies.

We still lack a similar simplifying assumption to parameterize strong interactions. In this paper, we take a step to remedy this by constructing a flexible yet manageable description of resonance interactions, making use of the idea that extra-dimensional (ED) models provide a description of strongly-interacting theories.

Exact results of such an equivalence between theories in different dimensions (the AdS/CFT correspondence [3, 4]) have only been obtained in particular cases. But for the purpose of LHC simulations, we do not need an exact duality to hold: we can study ED models whose essential parameters can be small while maintaining a nonzero coupling of fermions to light resonances (15). This coupling allows s-channel production of resonances, observable in the early stages of the LHC.

Conversely, in the fermiophobic case, discovery of the strongly-coupled sector is delayed to late stages of the LHC.

In this paper, we confine ourselves to Dynamical EWSB without a Higgs, but with light (≤ 1 TeV) spin-1 resonances coupled to the W⁺W⁻. Such light resonances can help unitarizing WW scattering while interacting weakly. We will consider only the lightest two triplets of resonances (W⁺₁₂, Z₁₂). An effective Lagrangian describing those resonances and their couplings to the SM would introduce O(100) new parameters. Using an ED description we drastically reduce the number of parameters involved to just four. We do not model the fermions in ED but choose the fermion-resonance coupling g_f/V as a free parameter³.

The triplets of resonances are described by ED gauge fields SU(2)_L ⊗ SU(2)_R propagating in a compact geometry given by ds^2 = w(z)^2(dx^2 + dz^2), where l₀ ≤ z ≤ l₁. We define two effective warp factors [12, 17] w_X = (l₀/z) exp \left( \frac{α_X}{\ln \frac{z-l₀}{l₁}} \right), X = A, V. The power in \left( \frac{z-l₀}{l₁} \right)^4 was based on walking technicolor arguments [18], but irrelevant for the LHC phenomenology: one can absorb the effect of a different power in the αX value. One can then extend minimally the setup to introduce U(1)_{B-L} and choose boundary conditions that preserve just U(1)_{em}, leading to a massless photon, and very light W, Z. Pure AdS geometry corresponds to αX = 0.

¹ In practice, only one very specific model of strong interactions has been implemented in Monte-Carlo generators and studied at Tevatron: the straw-man model [1].

² As opposed to the DBESS model, whose resonances are approximately decoupled from the electroweak sector [15].

³ Dealing with the intricacies of fermions in ED would provide an interesting picture of extended technicolor models [16].
We assume strong interactions are parity symmetric. Once coupled to the EW sector, physical mass eigenstates \((W_{1,2}^\pm, Z_{1,2})\) are an admixture of axial and vector eigenstates. Therefore, both triplets of resonances couple to the longitudinal \(W, Z\).

**Benchmark points:** Our description is very economical in terms of new parameters: the size of the ED \(\ell_1\), the amount of departure from rescaled-QCD \((\sigma_{V,A})\) and \(g_{jjV}\).

We emphasize that HTC is not a model of EWSB, rather it is an organizational scheme which allows us to describe viable resonance models in terms of a few parameters. To give a sample of the phenomenology coming out of this description, we chose two benchmark points in the parameter space, HTC1 and HTC2.

| Signal \(f_1(\text{TeV}^{-1})\) | \(\sigma_V\) | \(\sigma_A\) | \(g_{jjV} / g_2\) |
|-----------------------------|---------|---------|----------------|
| HTC 1                      | 6.3     | -10     | 0.01           |
| HTC 2                      | 8       | -22.5   | 0.05           |

For the point HTC1 above, \(M_{W_{1,2}} \approx (600, 680)\) GeV and width \(\Gamma_{W_{1,2}} \approx (4, 2)\) GeV. For HTC2, \(M_{W_{1,2}} \approx (500, 630)\) GeV and width \(\Gamma_{W_{1,2}} \approx (1, 4)\) GeV. Small \(\Gamma / M\) can be understood from a purely 4D point of view: HTC1 and HTC2 describe resonances as bound states of a strongly coupled theory, but whose interactions are determined by the number of colors, \(N_{\text{TC}}\), of the strong sector. Large values of \(N_{\text{TC}}\) correspond to weakly coupled (i.e. narrow) resonances. In the HTC1 point, both resonances are visible in the s-channel production to \(WZ\) and \(W\gamma\). The mass separation between the \(W_1\) and \(W_2\) is larger in HTC2, leading to a different phenomenology: only the lightest resonance is visible in the s-channel production to \(W\gamma\).

**Constraints:** The geometry parameters \(\sigma_V, \sigma_A\) \(\ell_1\) are constrained by LEP limits on anomalous triboson couplings \(0\). The \(g_{jjV}\) are constrained by direct \(Z', W'\) Tevatron cross section bounds \([13, 20]\) and by contact interaction limits \([3, 21]\). We have also checked that the resonances do not disrupt the measured Tevatron \(WZ, \gamma W\) cross sections \([22, 23]\) and high \(p_T\) distributions \([22, 24]\).

**s-channel production to \(WZ\):** We first consider \(s\)-channel production of a new vector resonance to \(W^\pm Z\) final state. Within the narrow width approximation (NWA), the signal cross section for each new resonance is

\[
\frac{1}{\sigma} \frac{d\mathcal{L}}{d\tau} L_{gg}^2 g_{jjV}^2 g_{VW_{1,2}}^2 \frac{M_{W_{1,2}}^2}{1152 M_W^2 M_{Z_{1,2}}^2 \Gamma_{W_{1,2}}^2} \left( 1 + \mathcal{O} \left( \frac{M_W^2}{M_{W_{1,2}}^2} \right) \right) , \tag{1}
\]

where \(s\) is the square of the LHC center of mass energy, \(g_{1}\) is a triboson coupling and \(\frac{d\mathcal{L}}{d\tau} = \int \frac{dx_1 f_q(x_1) f_{\bar{q}}(x_1)}{x_1^2} \bigg|_{x_1=1}^2\) \([25]\).

The fully leptonic decay mode \(W^\pm Z \rightarrow 3\ell + \nu, \ell = e, \mu\) is the cleanest mode and is not plagued by difficult QCD backgrounds. The important backgrounds for this process are, \(W^\pm Z \rightarrow 3\ell + \nu\) (irreducible), \(ZZ \rightarrow 4\ell, Z + b\bar{b} \rightarrow \ell^+ \ell^- + b\bar{b}\) and \(t\bar{t}\). All of the backgrounds were generated at parton level using ALPGENv13 \([20]\).

We implemented HTC into the event generator MadGraph \([27]\) and its add-on BRIDGE \([28]\). We modified both programs to handle anomalous triboson vertices. The parton level events were passed through PYTHIAv6.4 \([29]\) for parton showering, fragmentation, and hadronization, and then through PGS 4.0 \([30]\) for detector simulation\(^4\).

The standard minimal cuts we impose are: 1.) exactly 3 leptons with \(p_T > 10\) GeV, \(|\eta| < 2.5\). Of these leptons, at least one must have \(p_T > 30\) GeV, 2.) 2 same-flavor, opposite charge leptons reconstruct the \(Z\) mass to within \(3\) GeV, and 3.) \(H_{T,jets} < 125\) GeV, where \(H_{T,jets} = \sum_{jets} p_T, jets\). Cut 1.) reduces the background from \(ZZ\), while cuts 2.) and 3.) suppress the contribution from \(t\bar{t}\). The significance can be enhanced by cutting on the minimum \(p_T\) of the \(W\) and \(Z\) \((p_T > 100\) GeV). By assuming \(E_{\text{T,miss}} = p_T, \nu\) and constraining \((p_e + p_\mu)^2 = M_W^2\) we can solve for the \(z\) momentum of the neutrino\(^5\). This allows us to reconstruct the \(W\) momentum. See TABLE I for details.

\(^4\) We use the PGS ATLAS parameter set available with MADGRAPH4.0. The relevant parameters are the calorimeter segmentation \(\Delta\eta \times \Delta\phi = 0.1 \times 0.1\), the jet energy resolution \(\delta E / E_{\text{jet}} = 0.8 \sqrt{E}\), and the electromagnetic resolution \(\delta E / E_{\text{em}} = 0.1 / \sqrt{E} + 0.01\).

\(^5\) There is a two-fold ambiguity in \(p_x, \nu\) which we resolve by taking the solution with greater \(\vec{p}_z \cdot \vec{p}_\nu\).
Throughout this paper, cross sections include branching ratios to $\ell = e, \mu$ for signal and $t\bar{t}$ and $\ell = e, \mu, \tau$ for the other backgrounds. Detector effects, such as smearing and imperfect particle identification, are included in the efficiency quoted above. The most important detector effect in this channel is the lepton identification efficiency, $\sim 85\%$ in the kinematic region of interest.

Values of $g_{ffV}$ in HTC1,2 are compatible with TeVatron-LEP limits and still both peaks would be discovered within the first few fb$^{-1}$ at the LHC$^6$. However, the signal is very sensitive to the fermion-resonance couplings, $\propto g_{ffV}^2$, and thus very suppressed for fermiophobic models.

**s-channel production to $W\gamma$:** The second s-channel production final state we consider is $W^{\pm} \gamma \rightarrow \ell^{\pm} \nu \gamma$. Of the conventional three vector boson terms the only permutation consistent with $\mathcal{U}(1)_{em}$ gauge invariance is $g_{\gamma W_1 W_2} (\partial_{\mu} A_{\nu})(W_{12\mu} W_{2\nu}^+) + h.c.$, i.e. where the derivative acts on the photon field. A nonzero value for only one triboson coupling permutation is not possible in traditional, AdS-based Higgsless models. However, this final state as been considered recently $^{31}$ in the context of Low-Scale Technicolor (LSTC), exhibiting only one resonance.

The important backgrounds for this process are $W + \gamma$ (irreducible), $W +$ jet and $t\bar{t}$ (a jet faking a photon), and $\gamma +$ jets (jet fakes lepton). We use the rates $\sim 0.1\%$ for a jet to fake a photon, and $\sim 0.02\%$ for a jet to fake an electron $^{32}$. We apply the following cuts, 1.) Exactly 1 lepton, $p_T > 10$ GeV, $|y| < 2.5$, 2.) Exactly 1 photon, $p_T > 180$ GeV, $|y| < 2$, 3.) $p_{T,W} > 180$ GeV, 4.) Missing Energy $E_{T,\text{miss}} > 20$ GeV. See TABLE II for details.

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**TABLE I:** Processes, cross sections and efficiencies in the $WZ \rightarrow 3\ell + \nu$ mode after a cut on $p_T > 100$ GeV.

| Process                | $\sigma_{LO}$ (pb) | $\epsilon(\%)$ | $N_{EV}(\mathcal{L} = 10 \text{ fb}^{-1})$ |
|------------------------|---------------------|-----------------|------------------------------------------|
| HTC1 (WZ)              | 0.06                | 51              | 285                                      |
| HTC2 (WZ)              | 0.02                | 48.5            | 97                                       |
| $W^{\pm} Z \rightarrow 3\ell + \nu$ | 0.965              | 1.82            | 177                                      |
| $ZZ \rightarrow 4\ell$ | 0.116              | 1.56            | 18                                       |
| $Z\bar{b}$             | 11.4                | $5.17 \times 10^{-3}$ | 6                                        |
| $t\bar{t}$ (leptonic)  | 22.8                | $4.60 \times 10^{-4}$ | 10                                       |

**TABLE II:** Processes, cross sections and efficiencies for pp $\rightarrow \gamma W$ signal and background.

Both signals are dramatic, and would be seen within the first few fb$^{-1}$. If the resonances are separated by $\gtrsim 100$ GeV, as in HTC2, only the lightest resonance is visible because the decay modes $W_1 \rightarrow W_1 + Z, Z_1 + W$ are open suppressing the branching ratio to $W\gamma$. Conversely, HTC1 exhibits two resonances close in mass and both are visible in this channel.

Large s-channel signals to WZ and $W\gamma$ are familiar from LSTC $^{31}$. However, in the PYTHIA implementation of LSTC, techni-parity is imposed. Within this approximation only the vector resonance couples to WZ, and only the axial couples to $W\gamma$. This approximation does not hold in the HTC region of interest (viable with electroweak constraints).

**s-channel production of $Z_{1,2}$:** To discover the neutral partners one could use the dilepton or diboson channels: $pp \rightarrow Z_{1,2} \rightarrow \ell^{\pm} \ell^{-}, WW$. In the NWA, the ratio of dileptons to dibosons cross sections is $\frac{\sigma_{\ell\ell}}{\sigma_{WW}} \sim \frac{M_{W^0}}{M_{W^0}}$. For $g_{ffV} \simeq g_l$ and a 600 GeV resonance this ratio is almost 400. However the WW channel may not reveal both resonances. In the fully leptonic case $WW \rightarrow \ell\ell \nu\nu$ we cannot reconstruct the WW invariant mass, while in the semileptonic channel $t\bar{t}jj$ we have to deal with large backgrounds from $W +$ jets and $t\bar{t}$. Despite the smaller cross section ($\sigma \times BR \sim 1$ fb), the dilepton channel may reveal both resonances in the tens of fb$^{-1}$ range and allow for a more detailed study of resonance properties.

**Vector boson fusion:** The second process we investigate is Vector Boson Fusion (VBF). VBF will be important at the LHC regardless of the fermion-resonance coupling because it provides a window into $W_L W_L$ scattering. VBF has been studied at parton level for fermiophobic AdS-based Higgsless models in Ref. $^{33,44}$ where there is only one light resonance.

Although new final states can be considered in VBF like $pp \rightarrow W_{1,2} j j \rightarrow W_{1,2} \gamma j j$, we focus on the better studied $^{33,36,37,38,39,40}$ process $pp \rightarrow W_{1,2} + j j \rightarrow W_{1,2}^{\pm} + j j \rightarrow 3\ell + \nu + j j$. The backgrounds we consider are $W^{\pm} Z +$ jets, $Z Z +$ jets. The first background is irreducible, while the others come from either missing one of the leptons or a jet faking a lepton. Our initial cuts are very similar to the cuts used in $^{34}$: 1.) 3 leptons $p_T > 10$ GeV, $|y| < 2.5$, 2.) 2 jets, $p_T > 30$ GeV, $2 < |y| < 4.5$.
3.) $\Delta \eta_{jj} > 4$, 4.) $|m_{\ell\ell\ell} - m_Z| < 7.8$ GeV. After initial cuts, other backgrounds are negligible. To further enhance the significance we also apply a cut $p_{T, Z} > 70$ GeV.

In FIG. we plot the transverse cluster mass ($M_T = \sqrt{M^2(\ell\ell\ell) + p_T^2(\ell\ell\ell) + |E_{missT}|^2} - p_T(\ell\ell\ell) + E_{missT}^2$). Two edges are visible in HTC2 and one in HTC1. It is worth noticing here that PGS tagging efficiency for the VBF forward jets ($\sim 80\%$) is probably too optimistic for LHC at high luminosity.

| Process     | $\sigma \times BR \times \epsilon_{\text{final}}$ | $N_{EV}(L = 100\text{ fb}^{-1})$ |
|-------------|-------------------------------------------------|----------------------------------|
| HTC1        | 0.194 fb                                        | 19                               |
| HTC2        | 0.178 fb                                        | 18                               |
| $WZ + \text{jets}$ | 0.563 fb                                      | 56                               |
| $ZZ + \text{jet}$ | 0.049 fb                                          | 5                               |

TABLE III: Processes and efficiencies for VBF in the $3\ell + \nu + 2j$ channel. The following cuts $p_{T, Z} > 30$ GeV, $2 < |\eta| < 4.5$ and $\Delta R_{jj} > 4$ are applied at the parton level.

Other channels- $WZZ, W\gamma Z, W\gamma\gamma$: Within the HTC framework we are also able to study processes with more than two final state gauge bosons. These processes have two sources. The first is associated production of a Z (or $\gamma$) with a resonance which subsequently decays into $W^\pm Z(\gamma)$: $pp \rightarrow Z W_{1,2} \rightarrow WZZ$, etc. The second source is the direct production of a heavy resonance which has sufficient phase space to decay into a lighter resonance plus a SM gauge boson: $pp \rightarrow W^\pm Z \rightarrow W^\pm Z$. Associated production is familiar from fermiophobic Higgsless models [3]. Parton level studies have been performed in the $WZZ \rightarrow 4\ell jj$ channel, and although promising at parton level, the signal deteriorates once showering and detector effects are included. We estimate that 200-300 fb$^{-1}$ of luminosity is required for discovery and leave a more thorough study for future work.

Conclusions: To attack the parameter space of strong EWSB and perform LHC phenomenology, we use an economical parametrization of resonance interactions: Holographic Technicolor (HTC). The role of the 5D modelling here is to reduce the number of parameters to four, down from the $O(100)$ couplings possible in an effective Lagrangian of (two triplets of spin-1) resonances coupled to electroweak fields. HTC also allows us to effectively describe situations departing from rescaled QCD, as required by electroweak constraints.

These constraints still allow for light (500 or 600 GeV) resonances close by in mass (100 or 150 GeV separation) and sizeable direct couplings to SM fermion. We performed a collider study of two sample points (HTC1 and HTC2) in the parameter space of HTC. Both sample points exhibit early discovery of two light and nearby resonances via s-channel production to $WZ$ and $W\gamma$. The resonances also appear in VBF, though this requires higher luminosity.

In the future, we intend to provide a package based on MADGRAPH-BRIDGE to allow users to further navigate the parameter space. The framework presented here can be extended to add new particles, e.g. techni-ions, techni-omegas and composite Higgs.

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