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Benchmarks for new strong interactions at the LHC

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Abstract: 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.

Keywords: Technicolor and Composite Models, Hadronic Colliders.

JHEP05(2008)084

Contents

JHEP05(2008)084

1. 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 coupling.[1]

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.

[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].

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 properties are the same as those of strong interactions. This gives us a qualitative, and sometimes quantitative insight into strong interactions [5 − 7].

Since electroweak measurements [8, 9] exclude a rescaled copy of QCD (Technicolor [10, 11]), a departure from this rescaling is necessary. In the ED framework the departure can be described in terms of a few parameters. This is the idea behind Holographic Technicolor (HTC) [12].

2. Charting the unmapped territory

While HTC shares many features with purely-AdS models, such as approximate custodial SU(2) symmetry ($T \approx 0$), the freedom granted by non-AdS geometry allows for a suppression of the S parameter. In a pure AdS model, S can only be tamed by suppressing couplings between the resonance sector and the SM fermions (fermiophobic scenario) [13].[2] In HTC, because of cancellations between the nearly degenerate states, S 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 ($\lesssim$1 TeV) spin-1 resonances coupled to the W's.[3] Such light resonances can help unitarizing WW scattering while interacting weakly [17]. We will consider only the lightest two triplets of resonances ($W^{\pm}_{1,2}, Z_{1,2}$). An effective Lagrangian describing those resonances and their couplings to the SM would introduce $\mathcal{O}(100)$ 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_{ffV} as a free parameter.[4]

The triplets of resonances are described by ED gauge fields $\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$ propagating in a compact geometry given by $\mathrm{d}s^2 = w(z)^2(dx^2 - dz^2)$, where $l_0 \leqslant z \leqslant l_1$. We define two effective warp factors [19, 12] $w_X = (l_0/z)\exp\left(\frac{o_X}{2}\left(\frac{z-l_0}{l_1}\right)^4\right)$, $X = A, V$. The power in $(z/l_1)^4$ was based on walking technicolor arguments [20], but irrelevant for the LHC phenomenology: one can absorb the effect of a different power in the o_X value. One can then extend minimally the setup to introduce $U(1)_{B-L}$ and choose boundary conditions

[2] The autors in [14] pointed out that parts of the HTC region with negative S cannot be accommodated in an AdS model where the sole source of conformal breaking is by bulk bifundamentals. This is similar to the situation of Holographic QCD with $N_f = 3$, where m_s effects cannot be realized solely as a bulk vev (*Erlich et al, in preparation*).

[3] As opposed to the DBESS model, whose resonances are approximately decoupled from the electroweak sector [16].

[4] Dealing with the intricacies of fermions in ED would provide an interesting picture of extended technicolor models [18].

Signal	$\ell_1(\mathrm{TeV}^{-1})$	o_V	o_A	g_{ffV}/g_2
HTC1	6.3	-10	0	0.1
HTC2	8	-22.5	0	0.05

Table 1: Input parameters chosen for the two sample points (HTC1 and HTC2) used throughout the paper.

that preserve just $U(1)_{\mathrm{em}}$, leading to a massless photon, and very light W, Z. Pure AdS geometry corresponds to $o_X = 0$.

We assume strong interactions are parity symmetric. Once coupled to the EW sector, physical mass eigenstates $(W^{\pm}_{1,2}, Z_{1,2})$ are an admixture of axial and vector eigenstates. Therefore, both triplets of resonances couple to the longitudinal W, Z.

3. Benchmark points

Our description is very economical in terms of new parameters: the size of the ED (l_1), the amount of departure from rescaled-QCD ($o_{V,A}$) and the coupling to fermions (g_{ffV}).

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.

For the point HTC1 of table 1, $M_{W_{1,2}} \sim (600, 680)$ GeV and width $\Gamma_{W_{1,2}} \sim (4, 2)$ GeV. For HTC2, $M_{W_{1,2}} \sim (500, 630)$ GeV and width $\Gamma_{W_{1,2}} \sim (1, 4)$ GeV. Small $\frac{\Gamma}{M}$ 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_{TC}, of the strong sector. Large values of N_{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 $W\gamma$.

4. Constraints

The geometry parameters o_V, o_A l_1 are constrained by LEP limits on anomalous triboson couplings [9]. The g_{ffV} are constrained by direct Z', W' Tevatron cross section bounds [21, 22] and by contact interaction limits [23, 9]. We have also checked that the resonances do not disrupt the measured Tevatron $W\,Z$, γW cross sections [24, 25] and high p_T distibutions [24, 26].

5. s-channel production to WZ

We first consider $\hat{s}$-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

Process	$\sigma_{0,LO}$	$\epsilon(\%)$	$N_{\rm EV}(\mathcal{L}=10\,{\rm fb}^{-1})$
HTC1 (WZ)	0.06 pb	51	285
HTC2 (WZ)	0.02 pb	48.5	97
$W^{\pm}Z \to 3\ell+\nu$	0.965 pb	1.82	177
$ZZ \to 4\ell$	0.116 pb	1.56	18
$Zb\bar{b}$	11.4 pb	5.17×10^{-3}	6
$t\bar{t}$ (leptonic)	22.8 pb	4.60×10^{-3}	10

Table 2: Processes, cross sections and efficiencies in the $WZ \to 3\ell+\nu$ mode after a cut on $p_T > 100\,\text{GeV}$.

resonance is

$$\left(\frac{1}{s}\frac{d\mathcal{L}}{d\tau}\right)\frac{g_{ffV}^2 g_1^2 M_{W_{1,2}}^5}{1152 M_W^2 M_Z^2 \Gamma_{W_{1,2}}}\left(1+\mathcal{O}\left(\frac{M_W^2}{M_{W_{1,2}}^2}\right)\right), \tag{5.1}$$

where s is the square of the LHC center of mass energy, g_1 is a triboson coupling and $\frac{d\mathcal{L}}{d\tau} = \int \frac{dx_1}{x_1} f_q(x_1) f_{\bar{q}}(\frac{M_\rho^2}{x_1 s})$ [27].

The fully leptonic decay mode $W^{\pm}Z \to 3\ell+\nu$, $\ell = e, \mu$, is the cleanest mode and is not plagued by difficult QCD backgrounds. The important backgrounds for this process are, $W^{\pm}Z \to 3\ell+\nu$ (irreducible), $ZZ \to 4\ell$, $Z + b\bar{b} \to \ell^+\ell^- + b\bar{b}$ and $t\bar{t}$. All of the backgrounds were generated at parton level using ALPGENv13 [28].

We implemented HTC into the event generator MadGraph [29] and its add-on BRIDGE [30]. We modified both programs to handle anomalous triboson vertices. The parton level events were passed through PYTHIAv6.4 [31] for parton showering, fragmentation, and hadronization, and then through PGS 4.0 [32] for detector simulation.[5]

The standard minimal cuts we impose are: *1.)* exactly 3 leptons with $p_T > 10\,\text{GeV}, |\eta| < 2.5$. Of these leptons, at least one must have $p_T > 30\,\text{GeV}$, *2.)* 2 same-flavor, opposite charge leptons reconstruct the Z mass to within $3\Gamma_Z$, and *3.)* $H_{T,jets} < 125\,\text{GeV}$, where $H_{T,jets} = \sum_{\rm jets} p_{T,jets}$. 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 ($p_T > 100\,\text{GeV}$). By assuming $E_{T,\rm miss} = p_{T,\nu}$ and constraining $(p_e + p_\nu)^2 = M_W^2$ we can solve for the $\hat{z}$ momentum of the neutrino.[6] This allows us to reconstruct the W momentum. See table 2 for details.

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.

[5] 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 $\delta E/E_{\rm jet} = 0.8/\sqrt{E}$, and the electromagnetic resolution $\delta E/E_{\rm em} = 0.1/\sqrt{E} + 0.01$.

[6] There is a two-fold ambiguity in $p_{z,\nu}$ which we resolve by taking the solution with greater $\widehat{p}_\ell \cdot \widehat{p}_\nu$

JHEP05(2008)084

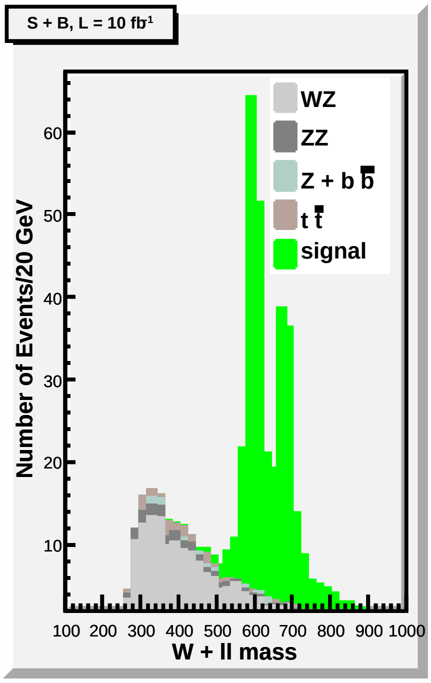

Figure 1: WZ channel for HTC1, $\mathcal{L} = 10\,\mathrm{fb}^{-1}$.

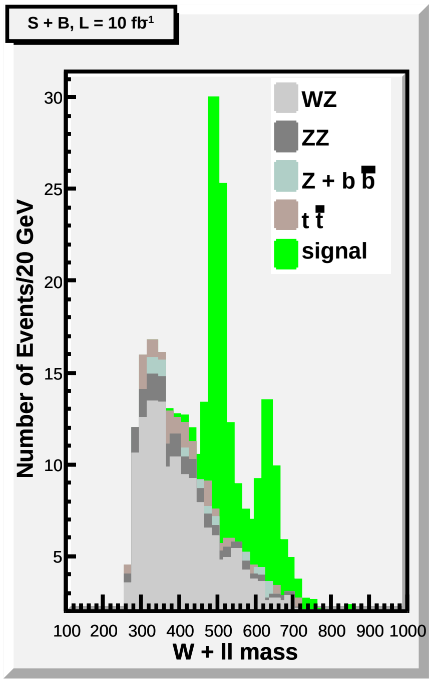

Figure 2: Same for HTC2.

Values of $g_{\rm ffV}$ 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.[7] However, the signal is very sensitive to the fermion-resonance couplings, $\propto g^2_{\rm ffV}$, and thus very suppressed for fermiophobic models.

6. 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 $U(1)_{\rm em}$ gauge invariance is $g_{\gamma W_{1,2}W}(\partial_{[\mu,}A_{\nu]}(W^-_{1,2[\mu}W^+_{\nu]}) + h.c.)$, 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 [33] 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 $\sim .02\%$ for a jet to fake an electron [34]. We apply the following cuts, 1.) Exactly 1 lepton, $p_T > 10\,\mathrm{GeV}, |\eta| < 2.5$, 2.) Exactly 1 photon, $p_T > 180\,\mathrm{GeV}, |\eta| < 2$, 3.) $p_{T,W} > 180\,\mathrm{GeV}$, 4.) Missing Energy $E_{T,\rm miss} > 20\,\mathrm{GeV}$. See table 3 for details.

Both signals are dramatic, and would be seen within the first few fb^{-1}. If the resonances are separated by $\gtrsim 100\,\mathrm{GeV}$, as in HTC2, only the lightest resonance is visible because

[7] We estimate the significance by $S/\sqrt{S+B}$, where we determine S and B by fitting each peak to a gaussian and counting the number of S and B events within twice the fitted width.

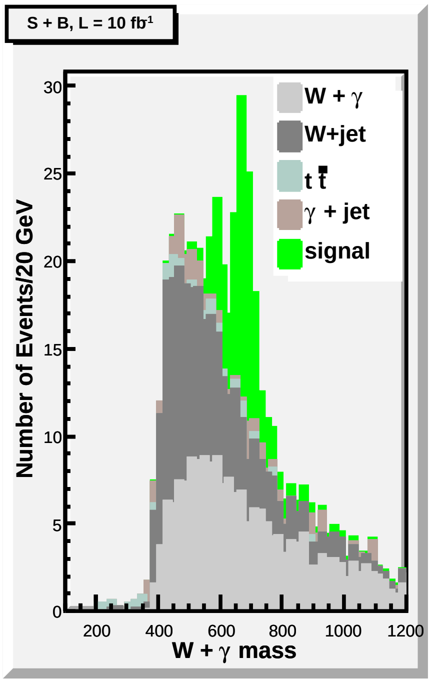

Figure 3: $W\gamma$ channel for HTC1, $\mathcal{L} = 10\,\text{fb}^{-1}$.

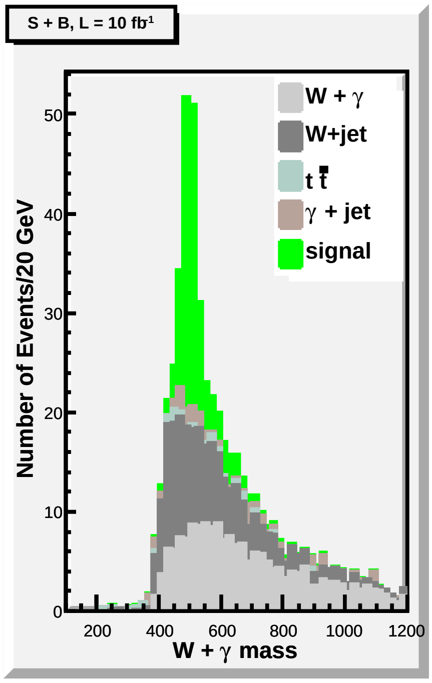

Figure 4: Same for HTC2.

Process	$\sigma_{0,LO}$	$\epsilon(\%)$	$N_{\text{EV}}(\mathcal{L} = 10\,\text{fb}^{-1})$
HTC1	0.015 pb	60	88
HTC2	0.03 pb	37	118
$W(\ell\nu) + \gamma$	3.84 pb	0.56	215
$W(\ell\nu)$ + jet ×fake rate	3.06 pb	0.28	86
tt (leptonic)	22.8 pb	0.005	12
γ + jet × fake rate	5.31 pb	0.044	25

Table 3: Processes, cross sections and efficiencies for pp $\to \gamma W$ signal and background.

the decay modes $W_2 \to W_1 + Z, Z_1 + W$ 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 [33]. 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).

7. s-channel production of $Z_{1,2}$

To discover the neutral partners one could use the dilepton or diboson channels: $pp \to Z_{1,2} \to \ell^+\ell^-, WW$. In the NWA, the ratio of dibosons to dileptons cross sections is $\frac{1}{8}\frac{g_1^2}{g_{ffV}^2}\left(\frac{M_{W_{1,2}}}{M_W}\right)^4$. For $g_{ffV} \simeq g_1$ and a 600 GeV resonance this ratio is almost 400. However

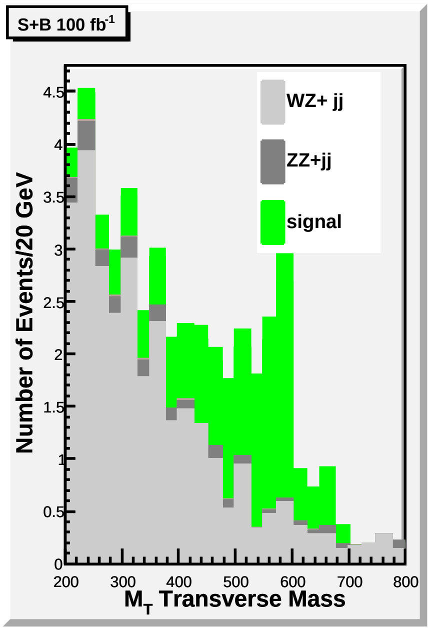

Figure 5: VBF channel $pp \to \mathrm{WZjj}$, ($\mathcal{L} = 100\,\mathrm{fb}^{-1}$) for HTC1.

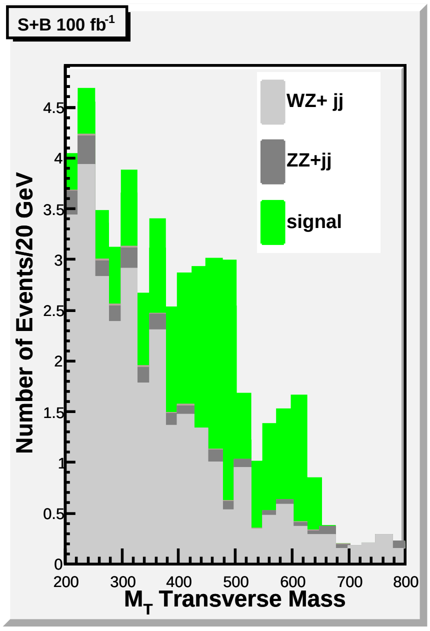

Figure 6: Same for HTC2.

the WW channel may not reveal both resonances. In the fully leptonic case $WW \to \ell\nu\ell'\nu'$ we cannot reconstruct the WW invariant mass, while in the semileptonic channel $\ell\nu jj$ we have to deal with large backgrounds from $W+\mathrm{jets}$ and $\bar{t}t$. Despite the smaller cross section ($\sigma \times \mathrm{BR} \sim 1\,\mathrm{fb}$), the dilepton channel may reveal both resonances in the tens of fb^{-1} range and allow for a more detailed study of resonance properties.

8. 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. [35, 36] where there is only one light resonance.

Although new final states can be considered in VBF like $pp \to W_{1,2}jj \to W\gamma jj$, we focus on the better studied [37 − 42] process $pp \to W_{1,2}+jj \to W^{\pm}Z+jj \to 3\ell+\nu+jj$. The backgrounds we consider are $W^{\pm}Z+\mathrm{jets}$, $ZZ+\mathrm{jets}$. 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 [36]: 1.) 3 leptons $p_T > 10\,\mathrm{GeV}, |\eta| < 2.5$ 2.) 2 jets, $p_T > 30\,\mathrm{GeV}, 2 < |\eta| < 4.5$, 3.) $\Delta\eta_{jj} > 4$, 4.) $|M_{\ell^+\ell^-} - M_Z| < 7.8\,\mathrm{GeV}$. After initial cuts, other backgrounds are negligible. To further enhance the significance we also apply a cut $p_{T,Z} > 70\,\mathrm{GeV}$.

In FIG. 5 we plot the transverse cluster mass [43] $M_T^2 = (\sqrt{M^2(\ell\ell\ell) + p_T^2(\ell\ell\ell)} + |E_{\mathrm{missT}}|)^2 - |p_T(\ell\ell\ell) + E_{\mathrm{missT}}|^2$. Two edges are visible in HTC2 and one in HTC1. It

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

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

is worth noticing here that PGS tagging efficiency for the VBF forward jets ($\sim 80\%$) is probably too optimistic for LHC at high luminosity.

9. 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 γ) with a resonance which subsequently decays into $W^{\pm}Z(\gamma)$: $pp \to ZW_{1,2} \to WZZ$, 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: $pp \to W_2^{\pm} \to W_1^{\pm}$Z. Associated production is familiar from fermiophobic Higgsless models [35, 36]. Parton level studies have been performed in the $WZZ \to 4\ell jj$ 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.

10. 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 $\mathcal{O}(100)$ 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-pions, techni-omegas and composite Higgs.

JHEP05(2008)084

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References

[1] K.D. Lane, *Technihadron production and decay rates in the technicolor straw man model*, hep-ph/9903372.

[2] S. Dimopoulos and H. Georgi, *Softly Broken Supersymmetry and* SU(5), *Nucl. Phys.* **B 193** (1981) 150.

[3] S.S. Gubser, I.R. Klebanov and A.M. Polyakov, *Gauge theory correlators from non-critical string theory*, *Phys. Lett.* **B 428** (1998) 105 [hep-th/9802109].

[4] E. Witten, *Anti-de Sitter space and holography*, *Adv. Theor. Math. Phys.* **2** (1998) 253 [hep-th/9802150].

[5] J. Erlich, E. Katz, D.T. Son and M.A. Stephanov, *QCD and a holographic model of hadrons*, *Phys. Rev. Lett.* **95** (2005) 261602 [hep-ph/0501128].

[6] L. Da Rold and A. Pomarol, *Chiral symmetry breaking from five dimensional spaces*, *Nucl. Phys.* **B 721** (2005) 79 [hep-ph/0501218].

[7] J. Hirn and V. Sanz, *Interpolating between low and high energy QCD via a 5D Yang-Mills model*, *JHEP* **12** (2005) 030 [hep-ph/0507049].

[8] B. Holdom and J. Terning, *Large corrections to electroweak parameters in technicolor theories*, *Phys. Lett.* **B 247** (1990) 88.

[9] Particle Data Group collaboration, W.M. Yao et al., *Review of particle physics*, *J. Phys.* **G 33** (2006) 1.

[10] S. Weinberg, *Implications of dynamical symmetry breaking: an addendum*, *Phys. Rev.* **D 19** (1979) 1277.

[11] L. Susskind, *Dynamics of spontaneous symmetry breaking in the Weinberg-Salam theory*, *Phys. Rev.* **D 20** (1979) 2619.

[12] J. Hirn and V. Sanz, *A negative S parameter from holographic technicolor*, *Phys. Rev. Lett.* **97** (2006) 121803 [hep-ph/0606086].

[13] G. Cacciapaglia, C. Csáki, C. Grojean and J. Terning, *Curing the ills of Higgsless models: the S parameter and unitarity*, *Phys. Rev.* **D 71** (2005) 035015 [hep-ph/0409126].

[14] K. Agashe, C. Csáki, C. Grojean and M. Reece, *The S-parameter in holographic technicolor models*, *JHEP* **12** (2007) 003 [arXiv:0704.1821].

[15] J. Hirn and V. Sanz, *The fifth dimension as an analogue computer for strong interactions at the LHC*, *JHEP* **03** (2007) 100 [hep-ph/0612239].

[16] R. Casalbuoni et al., *Degenerate BESS Model: the possibility of a low energy strong electroweak sector*, *Phys. Rev.* **D 53** (1996) 5201 [hep-ph/9510431].

JHEP05(2008)084

[17] R. Sekhar Chivukula, D.A. Dicus and H.-J. He, *Unitarity of compactified five dimensional Yang-Mills theory*, *Phys. Lett.* **B 525** (2002) 175 [hep-ph/0111016].

[18] N. Rius and V. Sanz, *Dynamical symmetry breaking in warped compactifications*, *Phys. Rev.* **D 64** (2001) 075006 [hep-ph/0103086].

[19] J. Hirn, N. Rius and V. Sanz, *Geometric approach to condensates in holographic QCD*, *Phys. Rev.* **D 73** (2006) 085005 [hep-ph/0512240].

[20] T.W. Appelquist, D. Karabali and L.C.R. Wijewardhana, *Chiral hierarchies and the flavor changing neutral current problem in technicolor*, *Phys. Rev. Lett.* **57** (1986) 957.

[21] CDF collaboration, T. Aaltonen et al., *Search for new physics in high mass electron-positron events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. Lett.* **99** (2007) 171802 [arXiv:0707.2524].

[22] CDF collaboration, A. Abulencia et al., *Search for W' boson decaying to electron-neutrino pairs in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev.* **D 75** (2007) 091101 [hep-ex/0611022].

[23] K.-M. Cheung, *Constraints on electron quark contact interactions and implications to models of leptoquarks and extra Z bosons*, *Phys. Lett.* **B 517** (2001) 167 [hep-ph/0106251].

[24] D0 collaboration, V.M. Abazov et al., *Measurement of the $p\bar{p} \to W\ \gamma + X$ cross section at $\sqrt{s} = 1.96$ TeV and $WW\gamma$ anomalous coupling limits*, *Phys. Rev.* **D 71** (2005) 091108 [hep-ex/0503048].

[25] CDF collaboration, A. Abulencia et al., *Observation of WZ Production*, *Phys. Rev. Lett.* **98** (2007) 161801 [hep-ex/0702027].

[26] CDF collaboration, *Searching for anomalous production of z-bosons with high transverse momentum in $0.94 fb^{-1}$ at the Tevatron*, CDF Note 8452.

[27] E. Eichten, I. Hinchliffe, K.D. Lane and C. Quigg, *Super collider physics*, *Rev. Mod. Phys.* **56** (1984) 579.

[28] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A.D. Polosa, *ALPGEN, a generator for hard multiparton processes in hadronic collisions*, *JHEP* **07** (2003) 001 [hep-ph/0206293].

[29] J. Alwall et al., *MadGraph/MadEvent v4: the new web generation*, *JHEP* **09** (2007) 028 [arXiv:0706.2334].

[30] P. Meade and M. Reece, *BRIDGE: branching ratio inquiry/decay generated events*, hep-ph/0703031.

[31] T. Sjöstrand, S. Mrenna and P. Skands, *PYTHIA* 6.4 *physics and manual*, *JHEP* **05** (2006) 026 [hep-ph/0603175].

[32] J. Conway, *PGS: Pretty Good Simulator*, online at http://www.physics.ucdavis.edu/conway/research/software/pgs/pgs4-general.htm.

[33] G. Azuelos et al., *Low-scale technicolor at the LHC*, in *Proceedings of the workshop Les Houches*, France (2007), to appear.

[34] CMS collaboration, *CMS technical design report, vol.* 2, CERN-LHCC-2006-001 (2006).

[35] A. Birkedal, K. Matchev and M. Perelstein, *Collider phenomenology of the Higgsless models*, *Phys. Rev. Lett.* **94** (2005) 191803 [hep-ph/0412278].

JHEP05(2008)084

[36] H.-J. He et al., *LHC signatures of new gauge bosons in minimal Higgsless model*, arXiv:0708.2588.

[37] A. Dobado, M.J. Herrero and J. Terron, *The role of chiral lagrangians in strongly interacting $W(l)W(l)$ signals at pp supercolliders*, *Z. Physik* **C 50** (1991) 205.

[38] J. Bagger et al., *LHC analysis of the strongly interacting W W system: gold plated modes*, *Phys. Rev.* **D 52** (1995) 3878 [hep-ph/9504426].

[39] A. Dobado and M.J. Herrero, *Testing the hypothesis of strongly interacting longitudinal weak bosons in electron-positron collisions at TeV energies*, *Phys. Lett.* **B 233** (1989) 505.

[40] A. Dobado, M.J. Herrero and J. Terron, *$W^{\pm}$ Z_0 signals from the strongly interacting symmetry breaking sector*, *Z. Physik* **C 50** (1991) 465.

[41] M.S. Chanowitz, *The no-Higgs signal: strong WW scattering at the LHC*, *Czech. J. Phys.* **55** (2005) B45 [hep-ph/0412203].

[42] J.M. Butterworth, B.E. Cox and J.R. Forshaw, *WW scattering at the LHC*, *Phys. Rev.* **D 65** (2002) 096014 [hep-ph/0201098].

[43] T. Han, *Collider phenomenology: basic knowledge and techniques*, hep-ph/0508097.

JHEP05(2008)084