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Warped Views on the Large Hadron Collider

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Models with warped extra dimensions, and their strongly coupled duals, offer a nice solution to the hierarchy problem and a very appealing realisation of flavour. Compatibility with the very stringent electroweak and flavour tests have made a generic picture emerge, with a composite Higgs, partial compositeness and custodial symmetry as the main ingredients. We review the main features of this picture and discuss how -and when- models with warped extra dimensions could be discovered at the Large Hadron Collider.

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1. Introduction

Models with warped extra dimensions [1] are a very interesting candidate for new physics at the TeV scale. They can stabilize the electroweak (EW) scale by means of gravitational red-shift and even shed light on other mysteries of our current understanding of particle physics, including the structure of flavor (see [2, 3] for early references, more recent work can be found in [4]) or dark matter [5], for instance. Furthermore, they provide weakly coupled duals to strongly coupled 4D models of electroweak symmetry breaking (EWSB) [6]. Indeed, even if one could argue that strong EWSB is much more general than the models which can be parameterized through warped extra dimensions, the ability to perform explicit calculation in the latter makes them an ideal playground to understand generic features of models of strong EWSB.

2. The New Standard Model from Warped Extra Dimensions

Models with warped extra dimensions, being dual to strongly coupled models, are likely to be very constrained by electroweak and flavor precision observables. In fact, even though the main model building ingredients were developed in some of the earliest works [3], it took several years to find a canonical model with all the required features. The model in question is a slice of AdS_5 space with metric

$$ds^2 = a^2(z)\left[\eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu - dz^2\right], \tag{2.1}$$

where the warp factor reads $a(z) = L_0/z$. The extra dimension is bounded by two three-branes, located at $z = L_0$ and $z = L_1$, and called UV brane and IR brane, respectively ($L_0 < L_1$). This metric is a solution of Einstein's equations provided the 5D cosmological constant and the brane tensions satisfy $\Lambda = -V_{UV}/L_0 = V_{IR}/L_0 = -24M^2L_0^{-2}$, where M is the 5D Planck mass [1]. The hierarchy problem is solved if all the 5D parameters (except for L_1) are of the order of the 4D Planck mass $\sim M_{\mathrm{Pl}}$, the Higgs is localized near the IR brane and we have the hierarchy $L_0/L_1 \approx \mathrm{TeV}/M_{\mathrm{Pl}}$. This hierarchy can in principle be generated with a mild fine-tuning by means of a bulk scalar [7]. Once the Higgs is localized close to the IR brane, fermion masses will be naturally hierarchical if they are allowed to propagate in the bulk of the extra dimension, with lighter Standard Model (SM) fermions being localized close to the UV brane and heavier (top and bottom) fermions being closer to the IR brane. This construction automatically produces hierarchical mixing angles and, thanks to the warping, an extra flavor protection that ensures flavor violation to scale with fermion masses or mixing angles [2, 4]. This scaling is typically enough to keep flavor observables under control (although some structure might be needed for full compatibility, see [4]). The reason for this is that the warping forces the lightest Kaluza-Klein (KK) excitations of bulk fields (and therefore the relevant new physics) to be localized close to the IR brane and therefore new physics effects are naturally sizable for heavy SM fields (which live close to the Higgs, thus the IR brane) and suppressed for light SM particles.

Tree level corrections to electroweak observables from the heavy Kaluza-Klein modes appear in the form of corrections to the SM gauge boson self-energies, to SM fermion gauge couplings and in the form of four-fermion interactions. If we assume the light fermions to be localized at the UV brane (which thanks to the warping is an excellent approximation), all these corrections turn out to be universal and can be encoded by means of field redefinitions in terms of the four oblique parameters of Ref. [8], $\hat{T}, \hat{S}, W, Y$. The final result (see [9] for a recent discussion of constraints on models with warped extra dimensions and their phenomenology) is that $\hat{T}$ is enhanced by the "volume" of the extra dimension $\log L_1/L_0 \approx \log M_{\rm Pl}/\mathrm{TeV} \approx 35$, whereas W, Y are volume suppressed. Assuming for instance a boundary Higgs, we have [9]

$$\hat{T}_{\rm bound.} = \frac{g'^2}{g^2}\frac{m_W^2 L_1^2}{2}\log\frac{L_1}{L_0}, \quad \hat{S}_{\rm bound.} = \frac{m_W^2 L_1^2}{2}, \quad W_{\rm bound.} = Y_{\rm bound.} = \frac{m_W^2 L_1^2}{4\log\frac{L_1}{L_0}}, \tag{2.2}$$

where g, g' are the $SU(2)_L \times U(1)_Y$ couplings and m_W is the W mass. If the Higgs is allowed to propagate in the bulk, $\hat{T}$ and $\hat{S}$ get a bit smaller whereas W and Y remain the same. For instance, using a quadratic profile for the Higgs we obtain

$$\hat{T}_{\rm Bulk} = \frac{1}{3}\hat{T}_{\rm bound.}, \quad \hat{S}_{\rm Bulk} = \frac{3}{4}\hat{S}_{\rm bound.}. \tag{2.3}$$

The only relevant exception to the universality of the new physics in these models comes with the bottom quark. Due to the heaviness of the top the left-handed doublet cannot be localized very close to the UV brane and therefore, b_L couplings receive in general sizable corrections. In fact the correction to the $Zb_L\bar{b}_L$ coupling is also volume enhanced (see [9]). Fortunately, both volume enhanced contributions can be canceled by means of a custodial symmetry [10] (see [11, 12] for possible alternatives), which consists of enlarging the SM gauge symmetry to

$$SU(2)_L \times U(1)_Y \to SU(2)_L \times SU(2)_R \times U(1)_X \times P_{L,R}, \tag{2.4}$$

where the last term is a discrete symmetry exchanging the left and right sectors. Thanks to the custodial symmetry $\hat{T}$ vanishes exactly at tree level (in the limit of UV localized light fermions) and so does also the volume enhanced correction to the $Zb_L\bar{b}_L$ coupling. The main constraints come then from the tree level contribution to $\hat{S}$ and the one loop (calculable) contributions to $\hat{T}$ and $Zb_L\bar{b}_L$. A detailed analysis [13] which included the most relevant one loop corrections to the EW precision observables (see [14] for an updated study) showed that, assuming flavor is explained by wave-function localization, the generic bound on new vector bosons in these models is

$$M_{\rm Gauge} \gtrsim 3.5 \text{ TeV}, \tag{2.5}$$

while new fermions can be sensibly lighter than that, provided the spectrum is rich enough [15].

3. Discovering Warped Extra Dimensions at the LHC

3.1 New Vector Resonances

New vector resonances are the smoking gun of warped extra dimensions/strong EWSB. However, the discussion in the previous section shows that in our canonical model with warped extra dimensions, the new bosonic resonances are not the typical Z'. They are relatively heavy and have suppressed couplings to light fermions, thus reducing their production cross section and their decay to leptons. Furthermore, their large coupling to heavy SM particles, mainly the top and the Higgs and longitudinal components of the EW bosons, makes them quite broad with widths that quickly approach a sizable fraction of their mass for multi-TeV masses. To make things even more

type	discovery limit (100 fb^{-1})	type	discovery $\mathscr{L}$ (mass)
Gluon	4 TeV [16]	top cust.	0.16-1.9 fb^{-1} (500 GeV)[24] | 100 fb^{-1} (1.5 TeV)[25]
Z'	2 TeV [17]	u, d cust.	1 fb^{-1}, $\sqrt{s} = 7$ TeV (1 TeV) [28]
W'	2 TeV [17]	u, d cust.	100 fb^{-1}, $\sqrt{s} = 14$ TeV (3-4 TeV) [28]
Coset	2 TeV (3 σ) [18]	τ cust.	300 fb^{-1} (480 GeV) [31]

Table 1: Discovery limit for different types of gauge boson and fermion KK modes in models with warped extra dimensions at the LHC. Unless otherwise stated the results are for $\sqrt{s} = 14$ TeV.

complicated (or interesting), the large mass of the vector resonances makes their decay products (t, H, V_L) highly boosted and therefore standard methods of top/Higgs/gauge boson reconstruction become very inefficient due to the strong collimation of their decay products.

Taking into account all these properties, several groups have studied the LHC reach for the vector resonances of models with warped extra dimensions, including Kaluza-Klein excitations of the gluons [16], charged and neutral EW bosons [17] and even gauge bosons of the coset space [18] characteristic of models in which the Higgs is a pseudo-Goldstone boson [19]. These analyses give the somewhat discouraging results collected in table 1. More sophisticated methods to deal with boosted objects [20] can result in an extra 0.5 TeV reach in the case of KK gluons. Also, current studies assume that the only open channels are into SM particles. As we will discuss in the next section, new fermionic resonances could be light enough to participate in the decays of the gauge boson KK modes, thus altering the result of the analyses presented here (see for instance [22]). The bottom line is that discovering the new bosonic resonances predicted by models with warped extra dimensions at the LHC will take time and ingenuity and might require an upgrade in energy or luminosity. Luckily, our canonical model with warped extra dimensions can accommodate and in fact it typically does, new light fermionic resonances, some of which can be much more easily (and much earlier) discovered at the LHC.

3.2 New Fermionic Resonances: Fermion Custodians

Due to the enlarged custodial symmetry, new fermionic resonances (fermion custodians) will come in these models in full multiplets of the custodial group. In order to avoid new exotic massless fermions, the corresponding 5D fields have twisted boundary conditions and can therefore result in ultra-light modes [21, 5]. These ultra-light modes are typically associated to heavier SM fields, whose zero modes are localized closer to the IR brane (in the 4D language they are typically associated to more composite SM fermions). Indeed, top custodians can be shown to naturally appear in many models of warped extra dimensions with custodial symmetry and play a crucial role in triggering EWSB and providing compatibility with EW precision tests [23, 13, 15]. Top custodians are new, relatively light vector-like quarks with a large coupling to the top and the SM gauge bosons or the Higgs. The production of these states at the LHC has been studied in [24] for pair production and [25] for single production with a result that just $0.16 - 1.9$ fb^{-1} of integrated luminosity (with $\sqrt{s} = 14$ TeV) should suffice to discover top custodians of mass $M = 500$ GeV in pair production and masses up to $M \approx 1.5$ TeV could be discovered through single production with 300 fb^{-1} (the details of the model can change slightly this ultimate reach in either direction).

We have argued that relatively light top custodians typically appear in models with warped extra dimensions. However, the extension of the custodial symmetry with the discrete P_{LR} symmetry, which has been used to protect the $Zb_L\bar{b}_L$ coupling, opens the door to light custodians for the lighter SM fermions, whose couplings can be protected by the same symmetry [26]. The possibility of light valence quark (u and d) custodians was considered for the first time in [27]. A specific realization consists of two degenerate vector-like electroweak doublets with hypercharges $7/6$ and $1/6$, respectively, with identical Yukawa couplings to the up quark and no further couplings to the SM fermions (in the basis in which all SM flavor mixing occurs in the charge $-1/3$ sector). Note that the apparently fine-tuned situation of exact degeneracy and equality of couplings can be the result of the custodial symmetry and in fact appears in some particular realizations of models with warped extra dimensions [13]. In this model, the SM quark couplings are not modified by operators of dimension six and the leading, dimension eight correction is suppressed by two powers of the up quark mass. Similarly, the first correction that violates flavor is proportional to the up quark mass and therefore under control (see [27] for details). This implies that the new quarks can be relatively light and have a large mixing with the up quark, which results in a large coupling to the SM gauge (or Higgs) bosons and the up quark. [1] This large coupling makes single production the best channel for discovery. An analysis of the Tevatron reach for such new quarks [27] shows that up to $M \approx 700$ GeV can be discovered with order one Yukawa couplings and 8 fb^{-1} integrated luminosity. The study of the LHC reach is currently under way but preliminary results show that the early run with 1 fb^{-1} at 7 TeV can be competitive or even improve on the Tevatron reach whereas masses of up to $3-4$ TeV could be discovered with 100 fb^{-1} and $\sqrt{s} = 14$ TeV [28].

Finally, the possibility of new fermion custodians is not restricted to quarks. In fact, it has been recently shown [29] that if an A_4 discrete symmetry is used to generate tri-bimaximal mixing in models with warped extra dimensions [30], the tau lepton might be more localized towards the IR brane than naively expected. The reason is that both the charged lepton Yukawa couplings and lepton flavor violation are suppressed by the scale of A_4 breaking and compatibility of the latter with observation implies an extra suppression on the lepton Yukawas which requires a stronger localization to reproduce the tau mass. This makes light tau custodians a natural occurrence in such models. The structure is identical to the one we have described for the up quark, with two new degenerate vector-like leptons which are doublets of the EW symmetry with hypercharges $-1/2$ and $-3/2$, respectively. The custodial symmetry again protects the tau couplings and we checked in [29] that both EW precision tests and flavor constraints are typically under control. The LHC reach for pair production of tau custodians has been recently studied in [31]. Each tau custodian decays into a SM gauge boson or the Higgs and a tau lepton. Requiring at least one of the custodians to decay into a leptonic Z, the two taus to decay also leptonically and the other boson to decay hadronically results in four leptons, two jets and missing energy in the final state. Note that, due to the large boost of the two taus, the event can be completely reconstructed assuming full collimation of the decay products, despite the four neutrinos in the final state. The large number of leptons in the final state, together with pair production of relatively heavy objects makes it easy to reduce the background to negligible levels. However, the small (EW) production cross section and

[1] These couplings are mildly constrained by the unitarity of the mixing matrices and by one loop contributions to the S parameter. For instance, the coupling of one of the charge $2/3$ new quarks to the Z and the up quark has to be $\lesssim 0.7g/(2c_W)$ with c_W the cosine of the weak angle [28].

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the reduction due to the leptonic branching fractions makes the reach, after 300 fb^{-1} at $\sqrt{s} = 14$ TeV, $M \approx 480$ GeV in this channel. The results for fermion custodian searches at the LHC are summarized in Table 1.

4. Conclusions and Caveats

Models with warped extra dimensions offer a nice solution to the hierarchy problem and a very appealing explanation of the flavor structure observed in nature. Electroweak and flavor constraints lead us to a canonical model with custodial symmetry and a relatively high scale (~ 3.5 TeV) of new bosonic resonances which are not easy to find at the LHC. The reason is that, besides being relatively heavy, they have small couplings to light SM fermions and therefore reduced production cross sections but strong coupling to the top and longitudinal EW gauge bosons, which makes them broad. Furthermore, they decay into boosted objects that require special techniques to be disentangled from the QCD background. Custodial symmetry, a natural ingredient in these models to tame large corrections to the T parameter and the $Zb_L\bar{b}_L$ coupling, imply the existence of new fermionic resonances, the fermion custodians, that can be light and couple strongly to the SM particles. Both top custodians and valence (up or down) quark custodians can be discovered very early at the LHC (and even at the Tevatron for the latter) if they are light enough. Tau custodians lighter than ≈ 500 GeV could be discovered at the LHC, although a large luminosity might be needed on the upper end of this mass range. Only after a long high energy (14 TeV) high luminosity (100-300 fb^{-1}) run the first colored vector resonances could be discovered whereas a much longer run would be needed for the discovery of electroweak new resonances.

The discussion in this talk has focused on one particular scenario with warped extra dimensions which, although arguably quite natural could be different from the one realized in nature. For instance, simple modifications of the background can lead to reduced electroweak and flavor constraints [32, 33] and therefore make discovery at the LHC much simpler in principle. Similarly, Higgsless models (see [34] and the first reference in [23]) which by giving up on the geometrical realization of flavor are compatible at tree level with a much smaller scale of new physics, will have a completely different phenomenology. Even custodial symmetry might be expendable in some constructions [12] in which new light fermionic resonances are not necessarily natural. Even in the class of models we have discussed, we could not cover all interesting implications at the LHC. In particular those related to new features in the Higgs and longitudinal gauge boson sector (see for instance [36, 35] and the last reference of [26]). The properties of all these models are worth studying in the light of the exciting times ahead of us.

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