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A 750 GeV Messenger of Dark Conformal Symmetry Breaking

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The tentative hints for a diphoton resonance at a mass of $\sim$ 750 GeV from the ATLAS and CMS experiments at the LHC may be interpreted as first contact with a "dark" sector with a spontaneously broken conformal symmetry. The implied TeV scale of the dark sector may be motivated by the interaction strength required to accommodate a viable thermal relic dark matter (DM) candidate. We model the conformal dynamics using a Randall-Sundrum type 5D geometry whose IR boundary is identified with the dynamics of the composite dark sector, while the Standard Model (SM) matter content resides on the UV boundary, corresponding to "elementary" fields. We allow the gauge fields to reside in the 5D bulk, which can be minimally chosen to be $SU(3)_c \times U(1)_Y$. The "dark" radion is identified as the putative 750 GeV resonance. Heavy vector-like fermions, often invoked to explain the diphoton excess, are not explicitly present in our model and are not predicted to appear in the spectrum of TeV scale states. Our minimal setup favors scalar DM of $\mathcal{O}$(TeV) mass. A generic expectation in this scenario, suggested by DM considerations, is the appearance of vector bosons at $\sim$ few TeV, corresponding to the gluon and hypercharge Kaluza-Klein (KK) modes that couple to UV boundary states with strengths that are suppressed uniformly compared to their SM values. Our analysis suggests that these KK modes could be within the reach of the LHC in the coming years.

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Only time will tell whether the current intense interest in the hints for a $\sim$ 750 GeV diphoton resonance, implied by the ATLAS [1] and CMS [2] data, is justified. While the statistics are not reliable yet, with currently $\sim 2\sigma$ and $\sim 1\sigma$ global significance from ATLAS and CMS, respectively, the simplicity of the diphoton final state may argue for some modest optimism, though any such attitude is not rigorously warranted. In any event, we adopt the more positive view of the potential hint and examine what it may signify.

The scale of the putative resonance is tantalizingly close to the electroweak scale and is aligned with expectations from "naturalness" of the Higgs mass. However, the dearth of evidence for the presence of massive electroweak states, W, Z, t, H, in the signal does not make a connection with electroweak symmetry breaking (EWSB) a natural inference. Nonetheless, the TeV scale can also be motivated from a very different perspective, namely the observation that interactions governed by TeV scale particles can lead to the correct order of magnitude abundance for the cosmic dark matter (DM); this is often referred to as the "WIMP" miracle. While there are many different possibilities that one can choose for the new physics, given the current hints, we will assume that the $\sim$ 750 GeV scale of the possible resonance is set by the dynamics of DM and is not directly related to the physics of EWSB (see also Ref. [3]).

Conformal symmetry breaking provides an interesting arena for generation of new mass scales and can often lead to the appearance of a "light" scalar, the dilaton, which could be its most accessible signal. Given this motivation, we will assume that the new resonance with mass $m_\phi \sim 750$ GeV is a dilaton of a dark sector, which includes DM. We will use a Randall-Sundrum (RS) type 5D background [4] to model the underlying physics, as a dual geometric description [5], in whose context the radion ϕ_D [6–8] is the aforementioned "dark" dilaton scalar. For other recent work on the radion interpretation of the 750 GeV diphoton excess, see also Ref. [9]. For a variety of alternative approaches see, for example, Ref. [10].

Given that current data suggests that the Standard Model (SM) is a weakly interacting theory, made up of elementary degrees of freedom, we will confine the matter content of the SM, including its Higgs sector, to the ultraviolet boundary of the warped RS geometry. We will allow the SM gauge sector to propagate in the 5D bulk [11]. In an minimal setup, it suffices to have only $SU(3)_c \times U(1)_Y$ in the bulk, which we will assume for now. The composite sector, corresponding to fields that are localized near or at the infrared (IR) boundary, are all assumed to be SM singlets, *i.e.* belong to a dark sector, which could naturally include DM (for an earlier work with a similar setup, see Ref. [12]). Note that this arrangement assumes that the physics of EWSB, flavor, and potentially other aspects of the SM are governed by the physics on the UV boundary whose cutoff scale is much larger than $\sim$ TeV. In particular, we will not address the issue of the Higgs potential naturalness, which may be associated with "elementary" UV dynamics.

In the above setup, the radion ϕ_D will not have significant interactions with the SM, except through "volume suppressed" couplings to the SM bulk gauge fields [8], from $SU(3)_c \times U(1)_Y$. Note that since we assume all SM matter to be confined to the UV boundary they do not generate the radion couplings through loop effects.

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In particular, our framework does not include vector-like quarks in its spectrum of single particle states [13], which is different from many models that attempt to explain the diphoton excess (see, for example, Refs.[14, 15]).

Let the curvature scale of the 5D warped background be denoted by k and the fifth dimension have length L. Note that identifying the UV scale as the Planck mass $M_P \sim 10^{19}$ GeV would require $kL \sim 30$, since the IR scale is given by $e^{-kL} \times$ UV scale. However, we may assume that the UV boundary has a cutoff that is much lower, but well above the weak scale, so that $kL \gg 1$. In a minimal setup, the couplings of the radion ϕ_D to the SM gauge fields may then be given by

$$\frac{\phi_D}{4kL\,\Lambda_D}(G^A_{\mu\nu}G^{A,\mu\nu} + B_{\mu\nu}B^{\mu\nu})\,, \tag{1}$$

where Λ_D is the decay constant of the radion and provides the IR cutoff scale; $B_{\mu\nu}$ and $G^A_{\mu\nu}$ are the hypercharge and color field strengths, respectively. For simplicity, we have chosen the underlying model parameters to obtain the above gauge-field independent interactions. (For example, by adjusting the bare and loop-induced radion couplings.) Since $B = \cos\theta_W\,\gamma - \sin\theta_W\,Z$, where θ_W is the weak mixing angle, the above interaction yields the coupling of ϕ_D to $\gamma\gamma$, $Z\gamma$, and ZZ, in the ratio $\cos^2\theta_W$, $-\sin\theta_W\cos\theta_W$, and $\sin^2\theta_W$, respectively.

We could also have $SU(2)_L$ in the bulk, by adding a $\phi_D W^I_{\mu\nu}W^{I,\mu\nu}$ term. With this term, using our parameterization, ϕ_D would couple universally to $\gamma\gamma$, ZZ and WW, and in particular the $Z\gamma$ coupling vanishes, indicating that the resonance will not show up in the $Z\gamma$ final state. Compared to the minimal setup, the branching ratio of $\phi_D \to \gamma\gamma$ is increased by about 30%, so to produce the correct signal strength other parameters of the model need to be modified at the $\sim 10\%$ level. Apart from this, there is no other significant difference in terms of collider phenomenology, and so in the following we focus on the minimal setup without a $\phi_D W^I_{\mu\nu}W^{I,\mu\nu}$ term.

The above interactions suffice to provide the production, through gluon fusion, and decay, into photons, of the purported new resonance. However, the ATLAS data shows some mild preference for a resonance of width ~ 45 GeV, though the evidence is not very strong. If we take this preference seriously, the interactions in Eq. (1) would not provide the needed width, since we expect $\Lambda_D \gtrsim m_\phi$ and $kL \gg 1$. However, there could in principle be a large number of new massive modes that correspond to the composite states, whose masses are generated by conformal symmetry breaking in the IR (near the TeV scale). These states are localized at the IR boundary and hence would couple to the radion only suppressed by $1/\Lambda_D$. If sufficiently many of these states are lighter than $m_\phi/2$, they may provide widths of $\mathcal{O}(45)$ GeV. Given that the evidence for the large width hypothesis is quite modest, we will instead focus on the possibility of a narrow width for ϕ_D and a minimal model content in our analysis.

The WIMP miracle motivates considering whether new dark composites can be good DM candidates in our scenario. Let us assume that the lightest such state with mass $\lesssim \Lambda_D$ is cosmologically stable due to some conserved charge or parity. We consider the cases of a Dirac fermion X or a real scalar χ, stabilized with a suitable unbroken symmetry, coupled to ϕ_D via [8, 16, 17]

$$-\frac{\phi_D}{\Lambda_D}(m_X\bar{X}X - \partial_\mu\chi\partial^\mu\chi + 2m_\chi^2\,\chi^2)\,. \tag{2}$$

As we will discuss later, one can achieve the correct relic abundance for DM, through pair annihilation into a pair of ϕ_D final states. The ϕ_D final states then decay promptly into the SM, in our minimal scenario.

While our model does not address the hierarchy problem, it still shares some of the signals of the warped RS-type hierarchy and flavor models. Namely, due to the presence of the SM gauge fields in the 5D bulk, one expects that Kaluza-Klein (KK) modes of these fields will appear at scales of order $\Lambda_D \sim$ TeV (see also Ref. [18]). In particular, a gluon KK state of a few TeV mass may well be within the reach of the LHC. To see this, note that the production of the gluon KK mode is very similar to the case of warped models with light fermions localized near the UV boundary, to explain their small masses (as in those models the Higgs is at the IR boundary). However, here, all quarks would couple to the KK gluon with the same strength and there is no preference for top quarks. Hence, the current bounds on RS KK gluons do not directly apply. However, with sufficient luminosity, one expects that KK gluons of mass $\mathcal{O}$(few TeV) could be within the reach the LHC. Other gauge KK modes will also appear at the same mass scale, however their production is suppressed by weak gauge couplings. In our scenario, their branching fraction into charged leptons is not suppressed compared to branching fractions into heavier SM states and they may also be interesting targets for future searches at the LHC. Below, we will examine the possibility of looking for the hypercharge KK mode of our minimal model in the clean dilepton (e^+e^- or $\mu^+\mu^-$) channel and find that it has discovery prospects comparable to that of the KK gluon. While generically present, the KK graviton - which is ~ 1.5 heavier than gauge KK modes in the RS model [19] - could potentially be outside the LHC reach.

Results: As mentioned before, we have assumed a minimal model that is consistent with a narrow scalar resonance at $\sim$ 750 GeV. To investigate collider phenomenology, we use MadGraph5_aMC@NLO [20], with NN23LO1 PDF set [21], and dynamical renormalization and factorization scales set to one half of transverse mass summed over all final states. For the scalar resonance we always include an NLO K-factor of ~ 1.2 (~ 1.4) at 8 (13) TeV, obtained by using the Higgs Characterisation model [22]. Our model is implemented in the UFO format [23] using the FeynRules package [24]. The width of ϕ_D and its branching ratios are computed with the MadWidth package [25].

We find that a signal strength of 5.9 fb, corresponding to an average between ATLAS and CMS [26], with integrated luminosities of 3.2 fb^{-1} and 2.6 fb^{-1} respectively, can be obtained if $kL\Lambda_D \approx 40$ TeV. Using the MadDM package [27], we found that the t-channel p-wave annihilation, $X\bar{X} \to \phi_D\phi_D$, will not readily yield an acceptable DM abundance, $\Omega h^2 \approx 0.12$ [28], unless its mass is chosen very close to $m_\phi/2$. In this case, resonant annihilation through s-channel ϕ_D exchange can then be sufficiently strong, but the required m_X is somewhat tuned. However, we find that a dark scalar χ from Eq. (2) can provide the correct thermal relic density if it has a mass $m_\chi \approx 1$ TeV, for $\Lambda_D \approx 5.5$ TeV. The diphoton signal strength then implies $kL \approx 7$, and the UV cutoff scale of the SM is hence given by $5.5 \times e^7 \sim 6000$ TeV, which corresponds to a "Little RS" geometry [29]. In this scenario, a KK gluon, g_{KK}, and a KK hypercharge gauge boson, B_{KK}, both of mass $\lesssim 5$ TeV, can be a reasonable expectation.

Parameters	Λ_D	5500 GeV
	kL	7.23
	m_ϕ	750 GeV
	M_χ	1040 GeV
	$M_{KK}^{g,B}$	3000 GeV
Widths	Γ_ϕ	0.012 GeV
	$\Gamma_{g_{KK}}$	46.4 GeV
	$\Gamma_{B_{KK}}$	12.7 GeV
Branching ratios	$\mathrm{Br}(\phi_D \to \gamma\gamma)$	6.54%
	$\mathrm{Br}(\phi_D \to ZZ)$	0.56%
	$\mathrm{Br}(\phi_D \to \gamma Z)$	3.81%
	$\mathrm{Br}(\phi_D \to gg)$	89.1%
	$\mathrm{Br}(g_{KK} \to q\bar{q})$	16.7%
	$\mathrm{Br}(B_{KK} \to l^+l^-)$	10.0%
Cross sections (LHC 14 TeV)	$pp \to g_{KK} \to t\bar{t}$	103 fb
	$pp \to g_{KK} \to jj$	550 fb
	$pp \to B_{KK} \to e^+e^-, \mu^+\mu^-$	1.2 fb

TABLE I: Benchmark point in the minimal model. Here q denotes a quark and l is a charged lepton, of any flavor.

A benchmark point is given in Table I with more details. This benchmark point could produce the correct signal strength and DM relic density. We have checked that this point is consistent with 8 TeV resonance searches in $\gamma\gamma$, γZ, ZZ, and jj final states [30–35]. In our simplified parametrization assumed in Eq. (1), the addition of $SU(2)_L$ in the bulk would suppress the γZ final state, which provides a test of our minimal setup. The UV brane SM matter has negligible interaction with the radion, and is practically irrelevant to collider phenomenology of ϕ_D. Furthermore, the KK gluon resonance in $q\bar{q}$ and $t\bar{t}$ final states, and the KK hypercharge mode in the dilpeton final state are consistent with 8 TeV (as well as 13 TeV for dileptons) searches [34, 36–38]. The coupling of the KK gauge fields to UV-localized fields is well-estimated by $1.2g/\sqrt{kL}$ in our model [39], where g is the relevant coupling constant. Note that for the branching ratios of the KK modes, we have neglected contributions from a gluon or hypercharge KK mode decaying into a gauge boson and a radion, which would change the total width at the $\sim$ percent level.

We find that at the 14 TeV LHC, the 3 TeV KK gluon can be produced in the $t\bar{t}$ final state, with a cross section of $\sim$ 100 fb, well above the reach for $t\bar{t}$ resonance search at 14 TeV, which is $\sim$ 10-20 fb in the all-hadronic channel with 300 fb^{-1} of integrated luminosity [40]. Assuming a $S/\sqrt{B}$ scaling, where S denotes signal and B is background, we estimate that the benchmark 3 TeV KK gluon can be discovered with $\mathcal{O}(10)$ fb^{-1} of integrated luminosity. Alternatively, the KK gluon can decay into two jets. With our benchmark coupling, discovery potential for a color octet vector in the di-jet final state can reach $\sim$ 4 TeV with 300 fb^{-1} of integrated luminosity [41]. Thus within this scenario, based on DM considerations, KK gauge fields can be expected to be within the reach of the 14 TeV LHC with $\mathcal{O}(10)$ or more fb^{-1} of integrated luminosity.

As for a 3 TeV KK hypercharge state, we find that the cross section for $pp \to B_{KK} \to$ dilepton at the 14 TeV LHC is about 1 fb, with negligible background [38]. Hence, for a handful of events, assuming an efficiency of $\sim 50\%$, we would need $\mathcal{O}(10)$ fb^{-1}. We then see that the prospect for discovery of the KK gluon in the $t\bar{t}$ and the KK hypercharge in the dilepton channels are comparable.

We note that our framework can trivially include bulk singlet fermions corresponding to right-handed neutrinos, localized near the IR boundary, to achieve natural Dirac masses for neutrinos [42]. Alternatively, we may include UV-boundary heavy Majorana neutrinos with masses near the cutoff scale, $M_N \lesssim 6 \times 10^3$ TeV, to yield seesaw masses for light neutrinos, assuming Yukawa couplings $\sim 10^{-4}$, similar to those of light SM fermions.

In conclusion, we have proposed that the $\sim$ 750 GeV diphoton excess, reported by ATLAS and CMS, can be due to a dilaton scalar, associated with dark conformal symmetry breaking. The dynamics of the conformal sector can also provide a DM candidate. Using a dual 5D RS-type geometric description, the requisite couplings of the "dark" radion, identified as the diphoton resonance, can be achieved by assuming that the gauge sector of the SM propagates in the 5D bulk. We assume that the rest of the SM corresponds to elementary fields that are localized at the UV boundary. We find that an IR-localized scalar of $\sim$ 1 TeV mass can be a suitable DM candidate if the scale that sets the coupling of the radion is about 5 TeV. In this setup, we may then expect that the KK gauge modes could be within the reach of the LHC Run II with $\mathcal{O}(10)$ fb^{-1} or more of integrated luminosity.

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