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Radion as a harbinger of deca-TeV physics

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Precision data generally require the threshold for physics beyond the Standard Model to be at the deca-TeV (10 TeV) scale or higher. This raises the question of whether there are interesting deca-TeV models for which the LHC may find direct clues. A possible scenario for such physics is a 5D warped model of fermion masses and mixing, with Kaluza-Klein masses $m_{\rm KK} \sim 10$ TeV, allowing it to avoid tension with stringent constraints, especially from flavor data. Discovery of a Standard-Model-like Higgs boson, for which there are some hints at $\sim$125 GeV at the LHC, would also require the Kaluza-Klein masses to be at or above 10 TeV. These warped models generically predict the appearance of a much lighter *radion* scalar. We find that, in viable warped models of flavor, a radion with a mass of a few hundred GeV and an inverse coupling of order $m_{\rm KK} \sim 10$ TeV could typically be accessible to the LHC experiments—with $\sqrt{s} =$ 14 TeV and $\sim$100 fb^{-1} of data. The above statements can be applied, *mutatis mutandis*, to 4D dual models, where conformal dynamics and a dilaton replace warping and the radion, respectively. Detection of such a light and narrow scalar could thus herald the proximity of a new physical threshold and motivate experiments that would directly probe the deca-TeV mass scale.

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I. INTRODUCTION

A main goal of experiments at the Large Hadron Collider (LHC) is the discovery of the mechanism for electroweak symmetry breaking. While electroweak symmetry breaking can be realized in a variety of ways in nature, the most economical possibility is through a Higgs doublet scalar H with a vacuum expectation value $\langle H \rangle \simeq 250$ GeV, as in the minimal Standard Model (SM). Based on precision electroweak data, it is widely expected that the SM Higgs mass $m_H \lesssim 160$ GeV [1,2]. To avoid violations of perturbative unitarity (the onset of strong interactions), the Higgs cannot be too heavy: $m_H \lesssim 1$ TeV [3,4].

The ongoing searches at the LHC have roughly yielded, at 95% confidence level, 115 GeV $\lesssim m_H \lesssim$ 130 GeV or else $m_H \gtrsim 500$ GeV [5,6], as of the time of the writing of this paper. Currently, both ATLAS [5] and CMS [6] report excess events, at about the 2σ level, that are consistent with a SM-like Higgs boson with a mass of $m_H \simeq 125$ GeV [7].

If the light Higgs signal at the LHC persists, one is compelled to think what new physics may help stabilize its mass against quadratic divergences that lead to the well-known hierarchy problem. An interesting possibility for such new physics is provided by 5D warped models of hierarchy and flavor, based on the Randall-Sundrum (RS) geometry [8]. The original RS model was introduced to address the hierarchy between $\langle H \rangle$ and the Planck scale $\bar{M}_{\rm P} \sim 10^{18}$ GeV. The inclusion of the SM gauge fields [9,10] and fermions [11] in the 5D RS bulk can result in a predictive framework for explaining the hierarchy and flavor puzzles simultaneously [11,12]. A natural expectation in this scenario is the emergence of various Kaluza-Klein (KK) resonances at the TeV scale.

While the simultaneous resolution of the Planck-weak hierarchy and flavor puzzle that warped models offer is highly attractive, it entails significant corrections to electroweak precision observables, in particular those related to the oblique T parameter, which result in constraining the KK-particle masses to above $\sim$10 TeV [13]. This of course means that there still remains a small hierarchy requiring some degree of tuning of $\mathcal{O}(10^{-3})$. Compliance with these bounds without tuned parameters requires an enlarged bulk gauge group to provide a custodial symmetry [14,15]. With this added complexity, the KK scale can be lowered to about 3 TeV [14–17] and the required tuning then becomes only around 10^{-2}. However, this setup then becomes considerably less economical, requiring extension from the $SU(2)_L$ gauge symmetry to $SU(2)_L \times SU(2)_R$ and an added set of new particles. Moreover, these interesting attempts end up facing further hurdles from the flavor sector, especially as the K-$\bar{K}$ mixing data [18] still constrain KK masses to be near or above 10 TeV [19,20], unless one resorts to some tuning [21,22] or some additional symmetries [23]. Therefore, by accepting a fine-tuning of $\mathcal{O}(10^{-3})$, corresponding to KK masses of order 10 TeV, one retains the attractive simplicity of the warped models that address SM flavor.

It has been pointed out in Refs. [24–26] that if the Higgs properties are established to be close to those in the SM, KK masses in warped models (with or without custodial symmetries) are pushed to scales of order 10 TeV, well

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beyond the reach of the LHC [27]. Hence, the confirmation of a SM-like Higgs state at the LHC would typically constrain $m_{\rm KK}$ to be well above the TeV scale, regardless of other precision data. Here, we note that while in Ref. [24] the Higgs signal is predicted to be enhanced by the effects of the warped KK states, Refs. [25,26] arrive at the opposite conclusion, namely, a suppressed Higgs signal. The analysis in Ref. [26] ascribes this discrepancy to the difference in the regularization methods employed by the authors of Ref. [24] in reaching their conclusions. We do not comment here on which procedure may be the correct approach. However, either way, it is clear that the effects of warped states would require a high KK mass scale, near 10 TeV, if significant departures from SM predictions for the Higgs production and decay rates are not detected at the LHC [28].

The above considerations suggest that the simplest warped models of hierarchy and flavor, especially those with a SM-like Higgs, would be naturally characterized by values of $m_{\rm KK}$ that lie outside the reach of the LHC. For example, if KK states are at the deca-TeV (10 TeV) scale, a simple and compelling picture of flavor can be obtained that can comply with the most severe flavor constraints, given the built-in RS Glashow-Iliopoulos-Maiani mechanism in these models [29,30]. Without a custodial symmetry, typically deviations from the precision bounds on the T parameter arise, albeit at modest levels for such a large KK mass scale. Therefore, if the Higgs turns out to be light, with $m_H \sim 125$ GeV, new deca-TeV physics may need a mild degree of custodial protection. However, without access to KK modes at the LHC, it may appear that we have achieved freedom from tension with flavor and electroweak constraints at the expense of experimental verifiability. We will argue below that this is not necessarily the case.

In this work, we note that deca-TeV warped scenarios typically include a light scalar, namely, the radion ϕ of mass $m_\phi \ll m_{\rm KK}$, that may be accessible to TeV-scale experiments, such as those at the LHC. The appearance of such a scalar, often referred to as the dilaton, is also likely common to all dynamical electroweak symmetry breaking theories that are holographically dual [31] to a warped model [32], i.e., 4D models that are characterized by conformal behavior above the KK scale [33–36]. The couplings of ϕ are suppressed by the scale of new dynamics (mass scale of heavy resonances). If measured, the signal rate in various decay channels of ϕ and its narrow width could provide estimates of the scale that suppresses the interactions of ϕ, offering clues about a new physical threshold near the deca-TeV scale. We note that the width of the radion in the regime studied in our paper is typically much smaller than the width of a SM Higgs of similar mass [37]. For other work on warped models with a decoupled KK sector ($m_{\rm KK} \gg 1$ TeV) see Refs. [38,39].

II. SETUP

We will adopt the usual RS background metric [8]

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2, \tag{1}$$

where k is the curvature scale, typically assumed smaller than the 5D fundamental scale M_5. The compact dimension y is bounded by ultraviolet (UV) and infrared (IR) branes at $y = 0$, L, respectively. The gauge and fermion content of the SM are placed in the 5D bulk. We will not require any other gauge symmetries beyond the SM $SU(3)_C \times SU(2)_L \times U(1)_Y$. The electroweak symmetry is assumed to be broken by an IR-brane-localized Higgs doublet.[1] The flavor structure of the SM can be obtained, using bulk fermions with nonzero vectorlike masses m_i, $i = u, d, \ldots$ [11,12]. The resulting zero-mode fermions are exponentially localized in 5D, parameterized by $c_i \equiv m_i/k$, with $c_i \sim 1$ for light fermions that are UV-localized and have small overlaps with the IR-localized Higgs.

The radion ϕ represents [42] quantum fluctuations of the position of the IR brane and interacts through its couplings to the trace of the energy-momentum tensor; these couplings are suppressed by the scale [43]

$$\Lambda_\phi \equiv e^{-kL}\sqrt{6M_5^3/k}. \tag{2}$$

The interactions of ϕ with bulk fields are derived in Ref. [44] and summarized in Ref. [37], to which we refer the interested reader for the relevant expressions and details [45]. In this work, for simplicity, we will not consider possible brane-localized kinetic terms, as their inclusion will not change our results qualitatively. We will also ignore Higgs-radion mixing (for an early discussion of this possibility see the third work in Ref. [45]). This mixing is proportional to $\langle H\rangle/\Lambda_\phi$ and for $\Lambda_\phi \sim 10$ TeV (as we have typically assumed in our work) it is a very small effect and can be ignored in our study. We note that interactions of the radion that are relevant to our analysis are governed by the low-energy states in the theory. Hence, the details of bulk gauge symmetries are not very important here, and our assumption of a SM bulk gauge content leads to conclusions that apply also to other more complicated scenarios. For some recent works on radion phenomenology see, for example, Ref. [46].

As a guide for phenomenology, we will consider the Goldberger-Wise mechanism [42,43], with a bulk scalar Φ of mass m and brane-localized potentials. The 5D vacuum expectation values of Φ on the UV and the IR branes are denoted by v_0 and v_L (with mass dimension 3/2), respectively. The stabilized radius L is then given by [42,43]

[1]We note that the bulk Higgs in warped gauge-Higgs unification models [40,41] receives 1-loop mass corrections cut off by KK masses and is less fine-tuned. However, these models are in general subject to the same severe tensions with the flavor data that push the KK scale to ~10 TeV.

$$kL = \epsilon^{-1} \ln(v_0/v_L), \tag{3}$$

where $\epsilon \equiv m^2/(4k^2)$ and

$$m_\phi^2 = \frac{v_L^2}{3M_5^3} \epsilon^2 \tilde{k}^2, \tag{4}$$

with $\tilde{k} \equiv k e^{-kL}$ the warped-down curvature scale.

III. ELECTROWEAK CONSTRAINTS

Various corrections resulting from the appearance of new states above the weak scale can be parametrized in terms of the oblique Peskin-Takeuchi (S, T) parameters [47] and we will discuss them below. Contributions from the tree-level mixing of the gauge zero modes with the heavy KK modes are given by [14]

$$S_{\text{tree}} \approx 2\pi(\langle H \rangle/\tilde{k})^2 \left[1 - \frac{1}{kL} + \xi(c)\right] \tag{5}$$

and

$$T_{\text{tree}} \approx \frac{\pi}{2\cos\theta_W^2} (\langle H \rangle/\tilde{k})^2 \left[kL - \frac{1}{kL} + \xi(c)\right], \tag{6}$$

where

$$\xi(c) \equiv \frac{(2c-1)/(3-2c)}{1 - e^{kL(2c-1)}} \left(2kL - \frac{5-2c}{3-2c}\right) \tag{7}$$

is a function of fermion localization parameter c and $\cos^2\theta_W \simeq 0.77$. For fermion profiles that lead to a realistic flavor pattern we have $\xi(c) \ll 1$.

In the absence of a 5D custodial symmetry, a UV-sensitive loop contribution to the T parameter arises. This dependence on the cutoff-scale physics can be *renormalized* by the addition of a higher-dimension operator. One can use naïve dimensional analysis relevant for strong dynamics [48] to estimate the size of the UV-sensitive contribution by

$$O_{\text{UV}} \sim \frac{(D^\mu H)^\dagger H (H^\dagger D_\mu H)}{\tilde{k}^2}, \tag{8}$$

where $\tilde{k}$ plays the role of the decay constant for a composite particle [41]. The contribution from the above operator to the T parameter can then be estimated by [14]

$$T_{\text{UV}} \sim \frac{1}{2\alpha} \left(\frac{\langle H \rangle}{\tilde{k}}\right)^2, \tag{9}$$

where α is the electromagnetic fine-structure constant. The results from Refs. [16,17] suggest that the loop contributions to the S parameter summed over the KK modes are not large, even for ~3 TeV KK masses they consider.

IV. RANGE OF PARAMETERS

We will assume that the Higgs is light: $m_H \sim 125$ GeV (other values in this range will also lead to nearly the same conclusions reached below). We now examine the expected sizes of δT and δS in the deca-TeV warped model considered in this work. For the sake of concreteness, let us consider $m_{\text{KK}} = 10$ TeV for bulk gauge fields, which implies $\tilde{k} \simeq 4$ TeV [9,10]. The value of kL determines the UV scale k in the RS geometry through $k = \tilde{k} e^{kL}$. We will consider a range of values bounded by $kL = 10$ and $kL = 30$. With $kL = 10$, we have $k \sim 10^5$ TeV, corresponding to a *little* RS scenario for flavor [49]; note that this value for k is sufficiently large that the resulting model can avoid conflict with even the most stringent flavor constraints [50]. For $kL = 30$, we get $k \sim 10^{16}$ GeV, close to $\bar{M}_{\text{P}}$ and similar to the original setup [8].

For the above choice of parameters, Eq. (5) then implies $\delta S \simeq 0.02$, and for $\delta T = T_{\text{tree}} + T_{\text{UV}}$, we find $\delta T \sim 0.3$–0.5 for $10 \leq kL \leq 30$. Hence, agreement with electroweak data [51] may require a bulk custodial symmetry or a somewhat larger KK scale. Alternatively, the Higgs could be heavy, say, above ~600 GeV [51,52]; one may consider this possibility if the present hints for a light Higgs do not persist with more data [7]. In any event, our main result—that a sole weak-scale radion (dilaton) can provide indirect evidence for KK (composite) states at scales as high as ~10 TeV—does not depend sensitively on the mass of the Higgs.

For simplicity, we will set $k = M_5$, which gives $\Lambda_\phi = \sqrt{6}\tilde{k}$; hence we will have $\Lambda_\phi \simeq m_{\text{KK}}$. Our choice for k is consistent with ignoring higher-order terms in 5D curvature $|R_5| = 20k^2$ [53], as assumed in derivation of the RS background [8], where the expansion parameter is R_5/M_c^2 and $M_c \sim \sqrt[3]{24}\pi M_5$ [54]. Since v_0 and v_L are 5D parameters, it is reasonable to assume that $v_{0,L} \sim k^{3/2}$ and $\ln(v_0/v_L) \sim 1$, which implies $\epsilon \sim (kL)^{-1}$, from Eq. (3). Using Eq. (4), one then finds $m_\phi \sim \tilde{k}/(kL)$. Hence, for $10 \leq kL \leq 30$ we may expect m_ϕ to be of order a few hundred GeV in our setup.[2]

V. RESULTS

The radion can be singly produced at the LHC via gluon fusion: $gg \to \phi$. The partonic cross section is given by

$$\hat{\sigma}(gg \to \phi) = \frac{\pi}{4} C_{gg}^2 \frac{m_\phi^2}{\Lambda^2} \delta(\hat{s} - m_\phi^2), \tag{10}$$

[2]If the IR brane tension is *detuned* significantly from the RS background value, the radion mass scaling can be changed to $m_\phi \sim \tilde{k}/\sqrt{kL}$ [55,56], in which case the radion could be somewhat heavier: $m_\phi \sim 500$–1000 GeV. The typical radion masses considered in our analysis may then require that the IR brane tension is somewhat tuned. In any event, these simple estimates ignore order-unity factors coming, for example, from the specific parameters of the stabilizing scalar potential. Hence, the mass range in our analysis may be relevant even in the case of large IR brane tension detuning, but this depends on the specifics of the stabilization mechanism that lie outside the scope of our phenomenological analysis. We thank K. Agashe for emphasizing these issues.

where $\sqrt{\hat{s}}$ is the partonic center-of-mass energy and $C_{gg} = -1/(4kL) - 23\alpha_s/(24\pi)$ if $m_\phi < 2m_t$. This may be compared to the cross section for production of a SM Higgs boson in the $m_t \to \infty$ limit [57]:

$$\hat{\sigma}(gg \to H) = \frac{\alpha_s^2}{576\pi}\frac{m_H^2}{v^2}\delta(\hat{s} - m_H^2), \tag{11}$$

where v is the vacuum expectation value of the Higgs field. Hence, in the regime of validity of the above equations, we have

$$\hat{\sigma}(gg \to \phi) = \left(\frac{12\pi C_{gg} v}{\alpha_s \Lambda}\right)^2 \hat{\sigma}(gg \to H). \tag{12}$$

The above equation suggests that $\hat{\sigma}(gg \to \phi) \sim 0.1\hat{\sigma}(gg \to H)$ for $kL = 30$ and $\Lambda_\phi = 10$ TeV. The Higgs production cross section via gluon fusion at the 14 TeV LHC for $m_H = 125$ GeV, for example, is about 50 pb [58], which includes a K factor of $\sim$2 from next-to-next-to-leading-order [59] and next-to-next-to-leading logarithm [60] corrections. We find that the corresponding leading-order cross section for $m_\phi = 125$ GeV is about 1.8 pb, which is consistent with the naïve expectation from Eq. (12).

Provided the radion is sufficiently heavy ($m_\phi \gtrsim 2m_W$), its dominant decay mode is to a pair of W bosons. See, for example, Fig. 1, illustrating the branching fractions of the radion for one choice of parameters.

We first consider a search for the radion in the WW channel at the LHC, following the planned energy upgrade to 14 TeV. In order to minimize QCD background, we take as our signal process the fully leptonic channel: $gg \to \phi \to W^+W^- \to l^+\nu_l l'^-\bar{\nu}_{l'}$, where l and l' may be either e or μ. We compute this process at leading order in the narrow-width approximation, using the CUBA library [61] for numerical integration. The irreducible background is the SM process $pp \to l^+l'^-\nu\bar{\nu}'$ (dominated by SM WW production), which we simulate using MADGRAPH 5 [62].

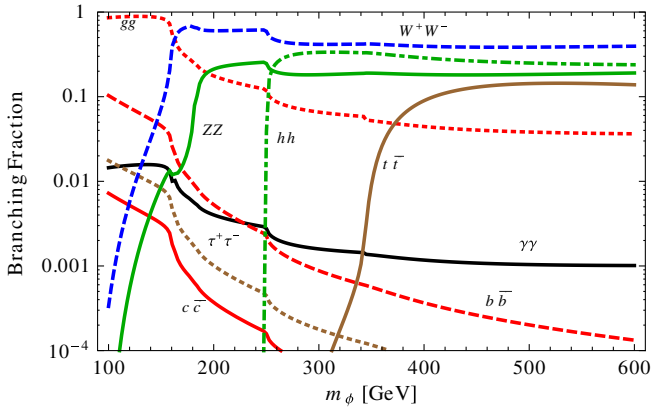

FIG. 1 (color online). Branching fractions of the radion as a function of radion mass, assuming $m_H = 125$ GeV, $kL = 10$, and $\Lambda_\phi = 10$ TeV.

Both signal and background are computed using the CT10 parton distributions [63].

We impose the following cuts, somewhat similar to those used in Higgs searches at the LHC [64,65]. We require exactly two oppositely charged leptons (e or μ), each with pseudorapidity $|\eta| < 2.5$, and no accompanying jets. One of the leptons must have transverse momentum $p_T > 20$ GeV, while the other must have $p_T > 15$ GeV. The two leptons must have an invariant mass $m_{ll} > 10$ GeV and be separated by $\Delta R > 0.4$, where $\Delta R \equiv \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2}$ is the separation in azimuthal angle φ and pseudorapidity η. When both leptons have the same flavor (e^+e^- or $\mu^+\mu^-$), we further require that $m_{ll} > 15$ GeV and $|m_{ll} - m_Z| > 15$ GeV, in order to suppress the Drell-Yan background. Additionally, we require large missing transverse energy $E_T^{\rm miss}$, which we identify as the vector sum of the neutrinos' transverse momenta: $E_T^{\rm miss} > 25$ GeV for $e^\pm\mu^\mp$ events and $E_T^{\rm miss} > 45$ GeV for e^+e^- and $\mu^+\mu^-$ events.

Finally, we consider a transverse mass variable m_T, defined by

$$m_T^2 \equiv \left(\sqrt{|\mathbf{p}_T^{ll}|^2 + m_{ll}^2} + E_T^{\rm miss}\right)^2 - |\mathbf{p}_T^{ll} + \mathbf{p}_T^{\rm miss}|^2, \tag{13}$$

where $\mathbf{p}_T^{ll}$ is the transverse momentum of the lepton pair, $\mathbf{p}_T^{\rm miss}$ is the missing transverse momentum, and $E_T^{\rm miss} = |\mathbf{p}_T^{\rm miss}|$ [65,66]. The definition of m_T is such that $m_T \leq m_\phi$ for all signal events. Because of this relation between m_T and m_ϕ, the distribution of m_T can be used to provide an estimate of m_ϕ. It may be possible to obtain an improved estimate by considering alternative transverse-mass variables that bound m_ϕ more tightly [67]. However, in this work we restrict our attention to m_T as defined in Eq. (13); in order to test for the presence of a radion with mass m_ϕ, we require that $m_\phi/2 < m_T < m_\phi$.

The model parameters relevant for this search are m_ϕ, Λ_ϕ, and kL. In Figs. 2–4, we show 3σ and 5σ contours in various slices of this parameter space, assuming 100 fb^{-1} of integrated luminosity at the LHC with a center-of-mass energy of 14 TeV. The significance is defined as $S/\sqrt{B}$, where S and B, respectively, denote the numbers of signal and background events surviving the cuts. The expected numbers of signal and background events are shown, for a few representative points in parameter space, in Table I.

For radion masses below the WW threshold, an important search channel is the diphoton final state, especially for smaller values of kL [37].[3] The observation of the radion signal in this channel would provide the value of m_ϕ through the reconstruction of the resonant peak. In

[3]We note that, for values of kL in the lower part of the range considered here, the branching fraction for $\phi \to \gamma\gamma$ tends to be significantly larger than the corresponding branching fraction of the SM Higgs; see Fig. 1.

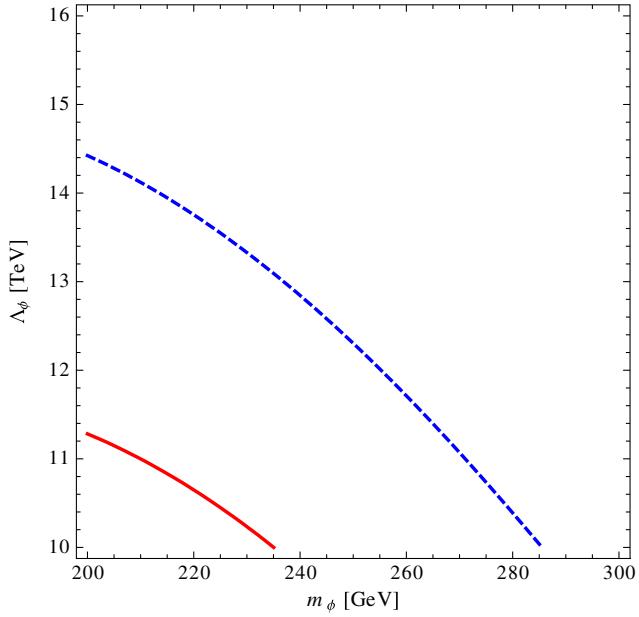

FIG. 2 (color online). The 3σ (dashed line) and 5σ (solid line) contours, in the (m_ϕ, Λ_ϕ) plane, for $\phi \to W^+W^- \to l^+l^-\nu\bar{\nu}$ at the LHC with 100 fb^{-1} at 14 TeV, with $kL = 10$.

Fig. 5, assuming $\Lambda_\phi = 10$ TeV, we have plotted the 3σ reach for this channel in the (m_ϕ, kL) plane, using the methodology of Ref. [37] and assuming 100 fb^{-1} of integrated luminosity at 14 TeV. We see that for $kL \lesssim 12$, significant evidence for a radion of mass in the range 100–160 GeV can be obtained. Therefore we find that,

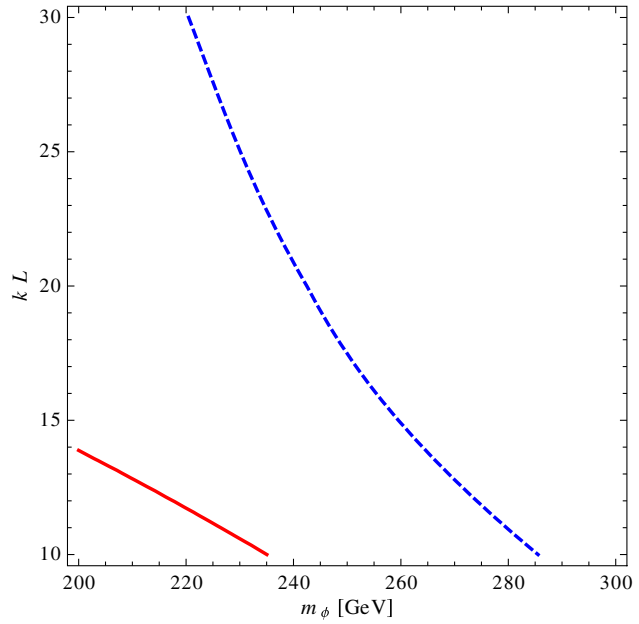

FIG. 3 (color online). The 3σ (dashed line) and 5σ (solid line) contours, in the (m_ϕ, kL) plane, for $\phi \to W^+W^- \to l^+l^-\nu\bar{\nu}$ at the LHC with 100 fb^{-1} at 14 TeV, with $\Lambda_\phi = 10$ TeV.

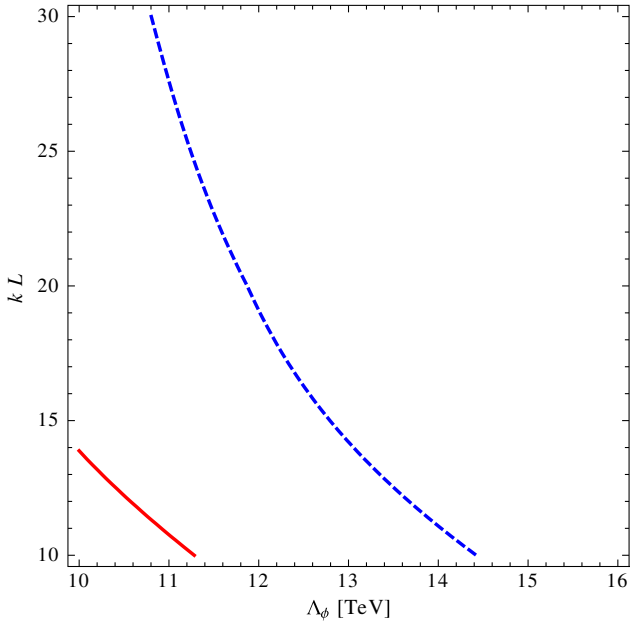

FIG. 4 (color online). The 3σ (dashed line) and 5σ (solid line) contours, in the (Λ_ϕ, kL) plane, for $\phi \to W^+W^- \to l^+l^-\nu\bar{\nu}$ at the LHC with 100 fb^{-1} at 14 TeV, with $m_\phi = 200$ GeV.

through the $\gamma\gamma$ and WW channels, the LHC has the potential to detect a radion signal over a healthy portion of parameter space, probing radion masses up to $m_\phi \sim 290$ GeV and scales as high as $\Lambda_\phi \sim 14$ TeV.

In case the current hints for a Higgs at about 125 GeV persist with more data, we see from Fig. 1 that $\phi \to hh$ is one of the dominant decay channels of the radion for $m_\phi \gtrsim 250$ GeV. If the Higgs is sufficiently SM-like, we may expect that each Higgs will mainly decay into a $b\bar{b}$ pair. This signal suffers from a large $4b$ jet QCD background [68]. While one may devise suitable cuts in order to make the $4b$ final state a useful search channel [69], looking for the radion using this final state will likely require improved analysis techniques and a detailed study, which lie outside the scope of this paper.

We close this section with a comment on the possibility of identifying the radion. If a narrow scalar is found at a few hundred GeV, in principle, measurements of its branching fractions could be a guide to its identity. For example, in the context of RS-like models of flavor, as

TABLE I. The expected numbers of signal and background events passing the cuts, and the significance $S/\sqrt{B}$, for selected values of model parameters, at the LHC with 100 fb^{-1} at 14 TeV.

m_ϕ/GeV	Λ_ϕ/TeV	kL	Signal	Background	$S/\sqrt{B}$
200	10	10	1.57×10^3	6.49×10^4	6.18
300	10	10	557	4.81×10^4	2.54
200	15	10	700	6.49×10^4	2.75
200	10	30	873	6.49×10^4	3.43

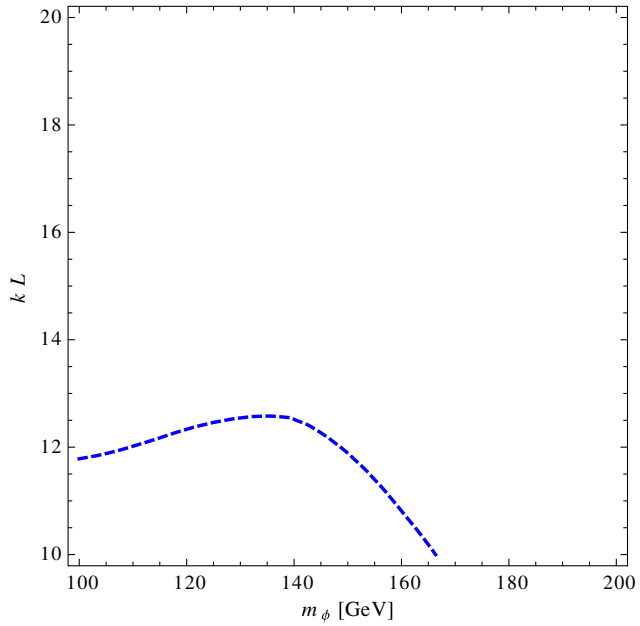

FIG. 5 (color online). The 3σ contour, in the (m_ϕ, kL) plane, for $\phi \to \gamma\gamma$ at the LHC with 100 fb^{-1} at 14 TeV, with $\Lambda_\phi = 10$ TeV.

examined here, we may expect a typical set of branching fractions comparable to those presented in our Fig. 1. However, it should be kept in mind that due to various model-dependent assumptions, one cannot make very precise statements here. What we have tried to demonstrate in our work is that, even if the scale of the new physics is at about 10 TeV, one may still have access to the radion signal and a hint for a nearby scale, in the class of models we have considered.

VI. CONCLUSIONS

In this work, we considered the possibility that the threshold for new phenomena may be at the deca-TeV (10 TeV) scale, as suggested by indirect precision measurements. In such a circumstance, one may ask whether there are physics scenarios that are governed by scales as high as 10 TeV but also include light signature states that are accessible at the LHC energies. Good examples of such scenarios are the 5D warped models of flavor based on the original RS background. The simplest versions of such models give rise to KK states whose masses are naturally pushed to scales of order 10 TeV, if they are to avoid disagreement with precision electroweak and flavor data. In order to lower the KK masses to a few TeV, these models must be augmented by a number of new gauge symmetries and large additions to their field content, leading to quite complicated setups. Discovery of a SM-like Higgs, hints for which may have been detected in the 2011 LHC data, will strengthen the case for a roughly 10 TeV lower bound on the KK threshold.

While the LHC will not have direct access to the deca-TeV KK states, we showed in this work that the radion scalar, associated with the quantum fluctuation of the compact fifth dimension, could very well be discovered at the LHC, with design parameters. We considered realistic warped flavor scenarios, characterized by UV scales $\sim 10^5$–10^{13} TeV and KK masses of $\sim$10–15 TeV. We focused on the gluon-fusion production of the radion. For $m_\phi > 2m_W$, we considered the typically dominant WW decay channel, followed by leptonic decays of each W. For $m_\phi < 2m_W$, we examined the utility of the diphoton channel in searching for the radion. Our analysis indicates that a radion of mass $\sim$100–300 GeV can be detected by the LHC experiments at the $\sim(3$–$5)\sigma$ level, for interesting parameter ranges of warped flavor models, assuming 14 TeV for the center-of-mass energy and $\sim$100 fb^{-1} of data. Other decay channels, such as $\phi \to WW \to l\nu jj$ and $\phi \to ZZ$, can be included in a more comprehensive analysis, leading to an improved reach. However, our results give a good estimate of the possibilities at the LHC. We also pointed out that, assuming a SM-like Higgs at $\sim$125 GeV, one may consider the $\phi \to hh \to b\bar{b}b\bar{b}$ signal for $m_\phi \gtrsim 250$ GeV, but this will likely require improvements in analysis techniques to control the large QCD background.

Our conclusions suggest that, through the production of a weak scale radion, experimental evidence for a warped deca-TeV threshold could be accessible at the LHC in coming years. Similar statements are applicable to dual 4D theories, with a dynamical scale around 10 TeV, whose spectrum is expected to include a light dilaton associated with spontaneous conformal symmetry breaking. In either picture, the discovery of a light and narrow scalar can herald the appearance of new physics at the deca-TeV scale, motivating new experiments at center-of-mass energies beyond that of the LHC.

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Note added.—After this work was completed and during the review process, ATLAS [70] and CMS [71] announced the discovery of a Higgs-like state at about 125 GeV. More data are required to determine, at a statistically significant level, whether this new state has properties that are different from those of the SM Higgs. However, the possibility of a heavy Higgs above $\sim$600 GeV, mentioned earlier in our discussion, is now strongly disfavored.

[1] LEP Electroweak Working Group, http://lepewwg.web.cern.ch/LEPEWWG/.
[2] GFitter Group, http://gfitter.desy.de/Standard_Model/.
[3] B. W. Lee, C. Quigg, and H. B. Thacker, Phys. Rev. Lett. **38**, 883 (1977).
[4] W. J. Marciano, G. Valencia, and S. Willenbrock, Phys. Rev. D **40**, 1725 (1989).
[5] G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **710**, 49 (2012).
[6] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **710**, 26 (2012).
[7] See the note added at the end of this paper.
[8] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999).
[9] H. Davoudiasl, J. L. Hewett, and T. G. Rizzo, Phys. Lett. B **473**, 43 (2000).
[10] A. Pomarol, Phys. Lett. B **486**, 153 (2000).
[11] Y. Grossman and M. Neubert, Phys. Lett. B **474**, 361 (2000).
[12] T. Gherghetta and A. Pomarol, Nucl. Phys. **B586**, 141 (2000).
[13] M. S. Carena, A. Delgado, E. Pontón, T. M. P. Tait, and C. E. M. Wagner, Phys. Rev. D **68**, 035010 (2003).
[14] K. Agashe, A. Delgado, M. J. May, and R. Sundrum, J. High Energy Phys. 08 (2003) 050.
[15] K. Agashe, R. Contino, L. Da Rold, and A. Pomarol, Phys. Lett. B **641**, 62 (2006).
[16] M. S. Carena, E. Ponton, J. Santiago, and C. E. M. Wagner, Nucl. Phys. **B759**, 202 (2006).
[17] M. S. Carena, E. Pontón, J. Santiago, and C. E. M. Wagner, Phys. Rev. D **76**, 035006 (2007).
[18] M. Bona *et al.* (UTfit Collaboration), J. High Energy Phys. 03 (2008) 049.
[19] C. Csáki, A. Falkowski, and A. Weiler, J. High Energy Phys. 09 (2008) 008.
[20] O. Gedalia, G. Isidori, and G. Perez, Phys. Lett. B **682**, 200 (2009).
[21] S. Casagrande, F. Goertz, U. Haisch, M. Neubert, and T. Pfoh, J. High Energy Phys. 10 (2008) 094; M. Bauer, S. Casagrande, U. Haisch, and M. Neubert, J. High Energy Phys. 09 (2010) 017.
[22] M. Blanke, A. J. Buras, B. Duling, S. Gori, and A. Weiler, J. High Energy Phys. 03 (2009) 001.
[23] M. Bauer, R. Malm, and M. Neubert, Phys. Rev. Lett. **108**, 081603 (2012).
[24] A. Azatov, M. Toharia, and L. Zhu, Phys. Rev. D **82**, 056004 (2010).
[25] F. Goertz, U. Haisch, and M. Neubert, Phys. Lett. B **713**, 23 (2012).
[26] M. Carena, S. Casagrande, F. Goertz, U. Haisch, and M. Neubert, J. High Energy Phys. 08 (2012) 156.
[27] See, for example, K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez, and J. Virzi, Phys. Rev. D **77**, 015003 (2008); A. L. Fitzpatrick, J. Kaplan, L. Randall, and L.-T. Wang, J. High Energy Phys. 09 (2007) 013; B. Lillie, L. Randall, and L.-T. Wang, J. High Energy Phys. 09 (2007) 074; K. Agashe, H. Davoudiasl, G. Perez, and A. Soni, Phys. Rev. D **76**, 036006 (2007); A. Djouadi, G. Moreau, and R. K. Singh, Nucl. Phys. **B797**, 1 (2008); K. Agashe, H. Davoudiasl, S. Gopalakrishna, T. Han, G.-Y. Huang, G. Perez, Z.-G. Si, and A. Soni, Phys. Rev. D **76**, 115015 (2007); O. Antipin, D. Atwood, and A. Soni, Phys. Lett. B **666**, 155 (2008); K. Agashe, S. Gopalakrishna, T. Han, G.-Y. Huang, and A. Soni, Phys. Rev. D **80**, 075007 (2009); H. Davoudiasl, T. G. Rizzo, and A. Soni, Phys. Rev. D **77**, 036001 (2008); H. Davoudiasl, S. Gopalakrishna, and A. Soni, Phys. Lett. B **686**, 239 (2010).
[28] See, also B. Lillie, J. High Energy Phys. 02 (2006) 019; A. Djouadi and G. Moreau, Phys. Lett. B **660**, 67 (2008); S. Casagrande, F. Goertz, U. Haisch, M. Neubert, and T. Pfoh, J. High Energy Phys. 09 (2010) 014; C. Bouchart and G. Moreau, Phys. Rev. D **80**, 095022 (2009); G. Cacciapaglia, A. Deandrea, and J. Llodra-Perez, J. High Energy Phys. 06 (2009) 054.
[29] K. Agashe, G. Perez, and A. Soni, Phys. Rev. Lett. **93**, 201804 (2004).
[30] K. Agashe, G. Perez, and A. Soni, Phys. Rev. D **71**, 016002 (2005).
[31] J. M. Maldacena, Adv. Theor. Math. Phys. **2**, 231 (1998); Int. J. Theor. Phys. **38**, 1113 (1999).
[32] See, for example, N. Arkani-Hamed, M. Porrati, and L. Randall, J. High Energy Phys. 08 (2001) 017; R. Rattazzi and A. Zaffaroni, J. High Energy Phys. 04 (2001) 021.
[33] W. D. Goldberger, B. Grinstein, and W. Skiba, Phys. Rev. Lett. **100**, 111802 (2008).
[34] J. Fan, W. D. Goldberger, A. Ross, and W. Skiba, Phys. Rev. D **79**, 035017 (2009).
[35] L. Vecchi, Phys. Rev. D **82**, 076009 (2010).
[36] T. Appelquist and Y. Bai, Phys. Rev. D **82**, 071701 (2010).
[37] H. Davoudiasl, T. McElmurry, and A. Soni, Phys. Rev. D **82**, 115028 (2010).
[38] Y. Bai, M. Carena, and E. Pontón, Phys. Rev. D **81**, 065004 (2010).
[39] H. Davoudiasl and E. Pontón, Phys. Lett. B **680**, 247 (2009).
[40] R. Contino, Y. Nomura, and A. Pomarol, Nucl. Phys. **B671**, 148 (2003).
[41] K. Agashe, R. Contino, and A. Pomarol, Nucl. Phys. **B719**, 165 (2005).
[42] W. D. Goldberger and M. B. Wise, Phys. Rev. Lett. **83**, 4922 (1999).
[43] W. D. Goldberger and M. B. Wise, Phys. Lett. B **475**, 275 (2000).
[44] C. Csáki, J. Hubisz, and S. J. Lee, Phys. Rev. D **76**, 125015 (2007).
[45] For early work on radion physics see, for example, C. Csáki, M. Graesser, L. Randall, and J. Terning, Phys. Rev. D **62**, 045015 (2000); U. Mahanta and S. Rakshit, Phys. Lett. B **480**, 176 (2000); G. F. Giudice, R. Rattazzi, and J. D. Wells, Nucl. Phys. **B595**, 250 (2001); S. Bae, P. Ko, H. S. Lee, and J. Lee, Phys. Lett. B **487**, 299 (2000); C. Csáki, M. L. Graesser, and G. D. Kribs, Phys. Rev. D **63**, 065002 (2001); J. L. Hewett and T. G. Rizzo, J. High Energy Phys. 08 (2003) 028; D. Dominici, B. Grzadkowski, J. F. Gunion, and M. Toharia, Nucl. Phys. **B671**, 243 (2003).
[46] V. Barger and M. Ishida, Phys. Lett. B **709**, 185 (2012); H. de Sandes and R. Rosenfeld, Phys. Rev. D **85**, 053003 (2012); K. Cheung and T.-C. Yuan, Phys. Rev. Lett. **108**, 141602 (2012); B. Grzadkowski, J. F. Gunion, and M. Toharia, Phys. Lett. B **712**, 70 (2012); H. Kubota and M. Nojiri, arXiv:1207.0621.

[47] M. E. Peskin and T. Takeuchi, Phys. Rev. D **46**, 381 (1992).
[48] H. Georgi, Phys. Lett. B **298**, 187 (1993).
[49] H. Davoudiasl, G. Perez, and A. Soni, Phys. Lett. B **665**, 67 (2008).
[50] M. Bauer, S. Casagrande, L. Gründer, U. Haisch, and M. Neubert, Phys. Rev. D **79**, 076001 (2009).
[51] GFitter Group, http://gfitter.desy.de/Oblique_Parameters/.
[52] M. E. Peskin and J. D. Wells, Phys. Rev. D **64**, 093003 (2001).
[53] H. Davoudiasl, J. L. Hewett, and T. G. Rizzo, Phys. Rev. D **63**, 075004 (2001).
[54] See, for example, the discussion in the fourth paper in Ref. [27].
[55] T. Konstandin, G. Nardini, and M. Quiros, Phys. Rev. D **82**, 083513 (2010).
[56] Y. Eshel, S. J. Lee, G. Perez, and Y. Soreq, J. High Energy Phys. 10 (2011) 015.
[57] H. M. Georgi, S. L. Glashow, M. E. Machacek, and D. V. Nanopoulos, Phys. Rev. Lett. **40**, 692 (1978).
[58] LHC Higgs Cross Section Working Group, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/.
[59] R. V. Harlander and W. B. Kilgore, Phys. Rev. Lett. **88**, 201801 (2002).
[60] S. Catani, D. de Florian, M. Grazzini, and P. Nason, J. High Energy Phys. 07 (2003) 028.
[61] T. Hahn, Comput. Phys. Commun. **168**, 78 (2005).
[62] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, J. High Energy Phys. 06 (2011) 128.
[63] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin, and C.-P. Yuan, Phys. Rev. D **82**, 074024 (2010).
[64] CMS Collaboration, Report No. CMS PAS HIG-11-024.
[65] ATLAS Collaboration, Report No. ATLAS-CONF-2012-012.
[66] A. J. Barr, B. Gripaios, and C. G. Lester, J. High Energy Phys. 07 (2009) 072.
[67] A. J. Barr, B. Gripaios, and C. G. Lester, Phys. Lett. B **713**, 495 (2012).
[68] T. Binoth, N. Greiner, A. Guffanti, J. Reuter, J.-P. Guillet, and T. Reiter, Phys. Lett. B **685**, 293 (2010); N. Greiner, A. Guffanti, T. Reiter, and J. Reuter, Phys. Rev. Lett. **107**, 102002 (2011).
[69] R. Lafaye, D. J. Miller, M. Mühlleitner, and S. Moretti, arXiv:hep-ph/0002238.
[70] G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **716**, 1 (2012).
[71] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **716**, 30 (2012).