On Light Dilaton Extensions of the Standard Model

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Abstract

We discuss the presence of a light dilaton in Conformal Field Theories (CFT) deformed by a nearly marginal operator, in the holographic realization consisting of confining Renormalization Group (RG) flows that end on a soft wall. Then, we apply this formalism to study the extension of the Standard Model (SM) with a light dilaton in a 5D warped model. We study the scalar and vector perturbations, compare the model predictions with Electroweak Precision Tests and find the corresponding bounds for the lightest modes. Finally, we analyze the possibility that the Higgs resonance found at the LHC can be a dilaton.

1. Spontaneous breaking of conformal invariance

Spontaneous breaking of Conformal Invariance (SBCI) leads to the existence of a non-zero value for the vacuum expectation value of the dilaton field. A CFT does not exhibit SBCI unless the theory is fine-tuned or supersymmetric. However, SBCI is possible in deformed CFT's, i.e.

$$\mathcal{L} = \mathcal{L}^{\rm CFT} + \lambda\mathcal{O}\,, \tag{1}$$

where $\mathcal{O}$ is a nearly marginal operator, i.e. $\dim(\mathcal{O}) = d - \epsilon$ with $\epsilon \ll 1$. This naturally leads to the existence of a light dilaton [1]. A holographic realization of this mechanism has been found in [2]. We consider a coupled scalar-gravitational system defined by the action

$$S_0 = M^{d-1}\int d^{d+1}x\sqrt{-g}\left(R - \frac{1}{2}(\partial_M\phi)^2 - V(\phi)\right)\,, \tag{2}$$

where ϕ is a scalar field. A *"domain wall"* geometry is a solution of the form

$$ds^2 = dy^2 + e^{-2A(y)}dx^\mu dx^\nu\eta_{\mu\nu}\,, \qquad \phi = \phi(y)\,. \tag{3}$$

We seek for solutions of the equations of motion with the near boundary expansion

$$\phi(y) = \underbrace{\lambda}_{\text{deformation}}\cdot e^{-\Delta y} + \underbrace{\langle\mathcal{O}\rangle}_{\text{condensate}}\cdot e^{-(d-\Delta)y} + \cdots\,, \qquad y \to +\infty\,. \tag{4}$$

The RG flows can be studied better with the holographic β-function, $\beta(\phi) := -\frac{\partial\phi}{\partial A}$. It obeys

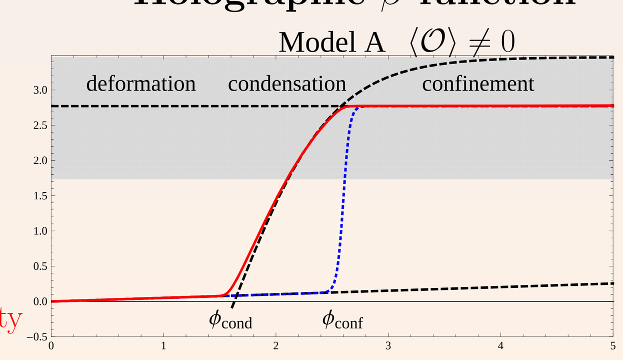
$$\beta\,\beta' = (\beta^2 - d(d-1))\left(\frac{\beta}{d-1} + \frac{1}{2}\frac{V'}{V}\right)\,, \tag{5}$$

where the integration constant is related to $\langle\mathcal{O}\rangle$ [2, 3].

We are interested in *confining flows* that are as regular as possible in the IR, i.e. those with a *Gubser's good IR singularity*. These conditions imply the IR limits

$$\beta(\phi) \to \beta_\infty \ \text{ with } \ \underbrace{\sqrt{d-1} <}_{\text{Confinement}} -\beta_\infty \underbrace{< \sqrt{d(d-1)}}_{\text{Good IR singularity}}$$

Holographic β-function



The flow has three different regimes: i) deformation in the UV, ii) condensate-dominated, and iii) confinement region in the IR.

2. Spectrum of excitations and type of dilatons

We include UV and IR branes in the action (2) located in (y_0, y_1), i.e.

$$S = S_0 - M^3\sum_\alpha\int d^4x dy\sqrt{-g}\,2\mathcal{V}^\alpha(\phi)\delta(y - y_\alpha)\,, \tag{6}$$

where $\mathcal{V}^\alpha$ $(\alpha = 0, 1)$ are the UV and IR 4D brane potentials, respectively. The scalar perturbations can be obtained from the equation of motion of the fluctuation modes F_n $(ds^2 \sim e^{-2(A+F)})$ [4]

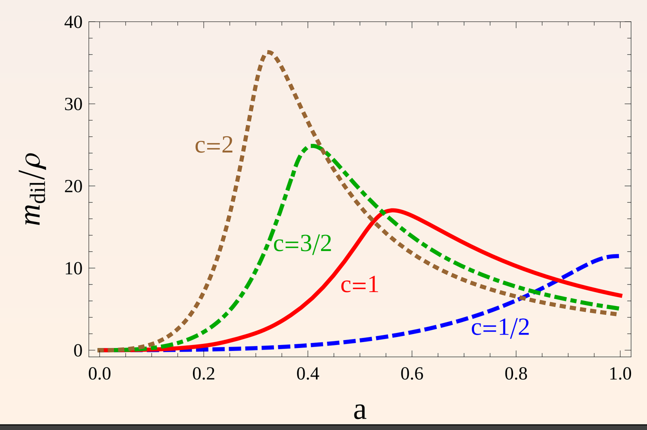
$$\ddot{F}_n - (d-2)\dot{A}\dot{F}_n - 2(d-2)\ddot{A}F_n - 2\frac{\ddot{\phi}}{\dot{\phi}}\dot{F}_n + 2(d-2)\dot{A}\frac{\ddot{\phi}}{\dot{\phi}}F_n = -e^{2A}m_n^2F_n\,, \tag{7}$$

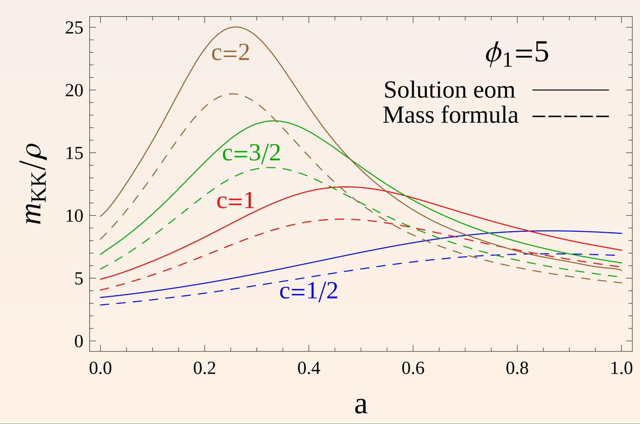
with brane-dependent boundary conditions, $\dot{F}_n|_{y_\alpha} = f(\mathcal{V}^\alpha, m_n)$. An approximate solution of (7) leads to a *mass formula* which allows to distinguish between two kind of light dilatons [2, 5]:

- Hard dilatons: those dominated by the value of β-function at the IR brane location [6].
- Soft dilatons: those dominated by the value of the β-function in the condensation scale. In this case one gets ($c > 0$ and its precise value depends on the particular model [2])

$$m^2_{\rm dil} \sim \beta^c_{cond}\Lambda^2_{\rm IR} \ \ll \ \Lambda^2_{\rm IR} \qquad \Longleftrightarrow \qquad \beta_{cond} \sim \Delta \ll \beta_\infty\,. \tag{8}$$

We consider the simplified model defined by $\beta(\phi) = -6ac\left[1 + e^{-a\phi}\right]^{-1}$, for which $\langle\mathcal{O}\rangle = 0$. The brane (potentials) dynamics have fixed (ϕ_0, ϕ_1) to solve the hierarchy problem: $A(\phi_1) - A(\phi_0) \simeq 35$. Then one gets the following behavior for the lowest scalar and KK vector modes ($\rho \equiv ke^{-35}$):





3. Electroweak breaking

We now consider the SM propagating in the 5D space described above. In addition to the 5D $SU(2)_L \times U(1)_Y$ gauge bosons, we define the SM Higgs as

$$H(x,y) = \frac{1}{\sqrt{2}}e^{i\chi(x,y)}\begin{pmatrix} 0 \\ h(y) + \xi(x,y)\end{pmatrix}\,, \tag{9}$$

where $h(y)$ is the Higgs background. The action of the model is [7]

$$S_5 = \int d^4x dy\sqrt{-g}\left(-\frac{1}{4}\vec{W}^2_{MN} - \frac{1}{4}B^2_{MN} - |D_MH|^2 - V(H)\right)\,. \tag{10}$$

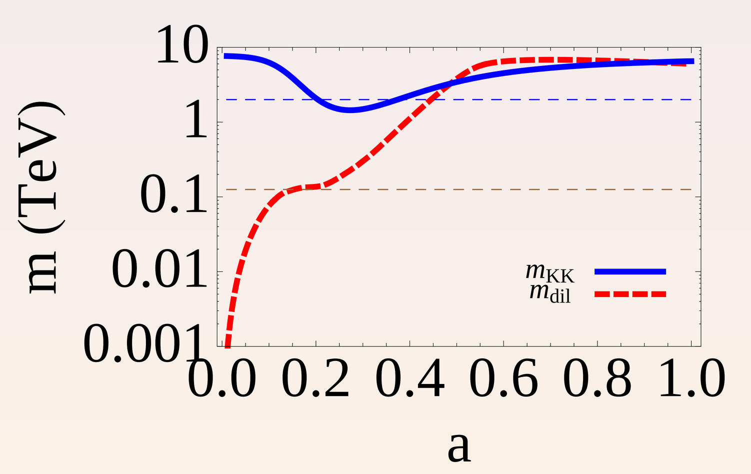
Electroweak symmetry breaking will be triggered on the IR brane.

To compare the model predictions with electroweak precision tests (EWPT) a convenient parameterization is using the (S, T, U) variables in [8, 7]. From the fitted values for S and T as [9]:

$$T = 0.05 \pm 0.07\,, \quad S = 0.00 \pm 0.08\,,$$

(90% correl.), one gets the result in the plot.

Bounds on KK and dilaton masses



We find a region in a such that $m_{KK} = \mathcal{O}(\text{TeV})$ and $m_{dil} \lesssim \mathcal{O}(100)$ GeV for $c = 1$. The realization of the dilaton for $a \lesssim 0.6$ ($\gtrsim 0.6$) is hard (soft). Other values of c lead to similar results.

4. Coupling of the radion to SM matter fields

A light dilaton has similar interactions with matter as the Higgs [4, 10], so we may wonder whether it can be a Higgs imposter. In this work we are assuming that the matter and Higgs fields are localized in the bulk. We are interested in the coupling of the radion $F(x,y) = F(y)\mathcal{R}(x)$ to massive gauge fields (W_μ and Z_μ), normalized as

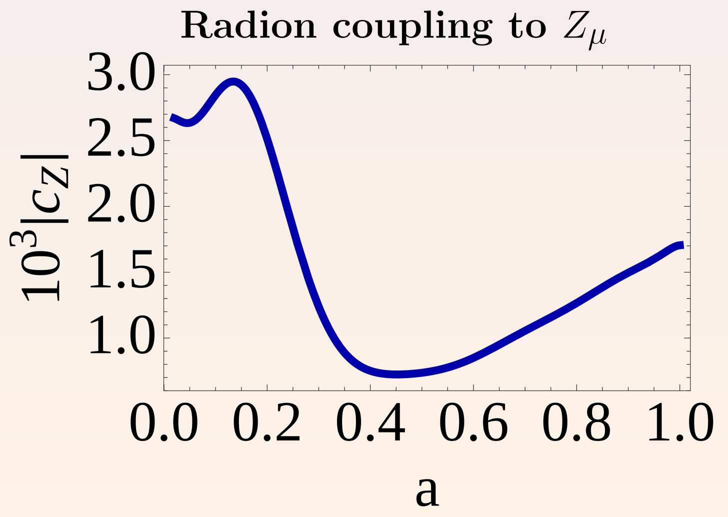
$$\mathcal{L}_V = \frac{r(x)}{v}\left\{2c_W\,m_W^2W_\mu W^\mu + c_Z\,m_Z^2Z_\mu Z^\mu\right\}\,, \tag{11}$$

where $v = 246$ GeV and $r(x)$ is the canonically normalized radion field. The case $c_W = c_Z = 1$ corresponds to the SM Higgs coupling. After expanding (10) to linear order in the perturbations, and using the massless radion approximation $F = e^{2A}$, one gets the result for c_V $(V = W, Z)$

$$|c_V| = 2\frac{v\,m_V^2}{\sqrt{6}e^{-A_1}M_P\rho^2}\left(\frac{\int e^{-2A}}{\int e^{2A-2A_1}}\right)^{1/2}ky_1\int_0^{ky_1}e^{4A-4A_1}\left(\frac{\int_0^y h^2e^{-2A}}{\int_0^{y_1}h^2e^{-2A}} - \frac{ky}{ky_1}\right)^2 d(ky)\,. \tag{12}$$

The numerical values of $|c_V|$ are very small so that the Higgs phenomenology (Higgs contribution to the unitarization of the V_LV_L elastic and inelastic scattering, the Higgs strengths,...) will be affected by a per mille effect. The tiny deviations with respect to the SM predictions would be unobservable at the LHC. For the same reason the possibility of a Higgs imposter is excluded for the present model.

Radion coupling to Z_μ



5. Conclusions

- We have studied a mechanism in holography that allows for naturally light dilatons in CFT's deformed by single trace deformations nearly marginal → Dilaton mass is controlled by the value of the β-function in the IR.
- The extension of the SM with a light dilaton in a 5D warped model leads to dilaton masses close to the Higgs mass, and KK vector masses of the order of TeV.
- A first study of the coupling of the radion to massive gauge fields suggests that the dilaton cannot be a Higgs imposter. However, some modifications of the warped model that would allow for a sizeable coupling are under study [5].
- The mechanism presented here could be extended and applied to other fields, in particular i) the study of the dilaton as a (light) Dark Matter candidate (additional symmetries may be required), and ii) the Cosmological Constant problem.

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