A Light Dilaton at the LHC

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A Light Dilaton: Motivation

- Electroweak Hierarchy Problem is one of the main theoretical motivations to go beyond the SM.
- One of the most studied and well motivated scenarios is the strongly interacting composite Higgs model. [Kaplan-Georgi,84']
- Composite Higgs models are holographic dual to the Randall-Sundrum (RS) like models in 5D warped extra dimensions. [Randall-Sundrum,hep-ph/9905221] [Agashe-Contino-Pomarol,hep-ph/0412089]

A Light Dilaton: Motivation

- However, the current LHC data puts strong constraints on the new physics (KK/composite modes, $m_{\rm KK} \gtrsim 3$ TeV) in these models.

  [CMS,1803.06292] [ATLAS,1804.10823]

- If the KK modes are above $\mathcal{O}(5)$ TeV, they might be out of the LHC reach.

- However, these strongly interacting theories may include a relatively light scalar, if the theory is approximately scale invariant.

- If the scale invariance is spontaneous broken at scale f then the corresponding (pseudo) Goldstone boson, the dilaton, may be much lighter than scale f.

A Light Dilaton: Motivation

- The dilaton mass, in general, is model dependent, i.e. it depends on the details of explicit breaking of the scale symmetry.
- It is argued that if the scale symmetry is explicitly broken by the operators which are very close to marginal, then the dilaton may remain light.

  [Contino-Pomarol-Rattazzi, talk by R. Rattazzi at Planck 2010, CERN]
  [Chacko-Mishra,1209.3022] [Bellazzini et al.,1209.3299] [Coradeschi et al.,1306.4601]
- For our phenomenological study we assume the dilaton mass is smaller than the spontaneous breaking scale, i.e. $m_\phi \ll f$.
- We consider dilaton in mass [10–300] GeV:
  - Below 10 GeV, there are generically constrained by flavour physics experiments.
  - Above 300 GeV, there are many studies in the literature.

    [see e.g. Ahmed et al.,1512.05771]

Effective theory of a dilaton

After EWSB the effective Lagrangian for the Higgs-dilaton system

$$\mathcal{L}_{\text{eff}}^{(2)} = \frac{1}{2}\partial_\mu h_0 \partial^\mu h_0 + \frac{c'_{\text{K}}}{2}\partial_\mu \phi_0 \partial^\mu \phi_0 - \frac{1}{2}m_{h_0}^2 h_0^2 - \frac{1}{2}m_{\phi_0}^2 \phi_0^2 - c_{\text{K}}\partial_\mu h_0 \partial^\mu \phi_0 - c_{\text{M}} m_{\phi_0}^2 h_0 \phi_0$$

- The c_{K} and c_{M} are the kinetic and mass mixings. The c'_{K} is a kinetic normalization coefficient.
- These mixings can be removed by rotating the scalar fields into the mass eigenstate basis (h,ϕ):

$$\begin{pmatrix} \phi_0 \\ h_0 \end{pmatrix} = \frac{1}{Z}\begin{pmatrix} \cos\theta & -\sin\theta \\ Z\sin\theta + c_{\text{K}}\cos\theta & Z\cos\theta - c_{\text{K}}\sin\theta \end{pmatrix}\begin{pmatrix} \phi \\ h \end{pmatrix}$$

where $Z \equiv \sqrt{c'_{\text{K}} - c_{\text{K}}^2}$ and θ is the mixing angle.

Effective theory of a dilaton

- In the low energy theory, the scale invariance is non-linearly realized.
- Such that the dilaton interactions with the SM fields are fixed by the symmetries.

Dilaton interactions with SM fields

$$\mathcal{L}_{\text{eff}}^{\text{int}} = \frac{\phi_0}{f}\Big[b_{\text{H}}\partial_\mu h_0 \partial^\mu h_0 - c_{\text{H}} m_{h_0}^2 h_0^2 - c_\psi^i m_{f_i} \bar{f}_i f_i + 2c_{\text{W}} m_W^2 W_\mu^+ W^{-\mu} + c_{\text{Z}} m_Z^2 Z_\mu Z^\mu$$
$$+ b_\gamma F_{\mu\nu} F^{\mu\nu} + 2b_{\text{W}} W_{\mu\nu}^+ W^{-\mu\nu} + b_{\text{Z}} Z_{\mu\nu} Z^{\mu\nu} + b_g G_{\mu\nu}^a G^{a\mu\nu} + 2b_{\gamma\text{Z}} F_{\mu\nu} Z^{\mu\nu}\Big]$$

- The coefficients b's and c's are model dependent.
- In the following, we consider two well motivated scenarios.

Models for a light dilaton

1. Bulk RS model
   - RS model is 5D warped extra dimensional model with two branes, UV and IR.
   - The low-energy effective 4D theory includes a radion with relatively small mass, which is identified as the dilaton in the holographic picture.
   - Only the SM Higgs doublet and right-handed top quark are on the IR brane, i.e. they are composite, whereas, the remaining light fermions and gauge bosons are in the bulk or UV localized, i.e. elementary states.

[Csaki et al.,0705.3844] [Chacko et al.,1411.3758]

2. Anomalous Dilaton
   - The dilaton interactions are only due to the running of gauge couplings, hence only interact to gauge boson kinetic terms.

Specific Models for the dilaton

couplings	bRS radion	anomalous dilaton
c_K	$6\frac{v}{f}\xi$	0
c'_K	$1+6\frac{v^2}{f^2}\xi$	1
c_M	0	0
c_W	$1-\frac{3\pi kR\,m_W^2}{f^2(k/M_{Pl})^2}$	0
c_Z	$1-\frac{3\pi kR\,m_Z^2}{f^2(k/M_{Pl})^2}$	0
b_W	$\frac{1}{4\pi kR}$	$\frac{\alpha}{8\pi s_W^2}b_2$
b_Z	$\frac{1}{4\pi kR}$	$\frac{\alpha}{8\pi t_W^2}(b_2+b_Y t_W^4)$
b_γ	$\frac{1}{4\pi kR}+\frac{\alpha}{8\pi}(b_2+b_Y)$	$\frac{\alpha}{8\pi}(b_2+b_Y)$
$b_{\gamma Z}$	$\frac{\alpha}{8\pi t_W}(b_2-b_Y t_W^2)$	$\frac{\alpha}{8\pi t_W}(b_2-b_Y t_W^2)$
b_g	$\frac{1}{4\pi kR}+\frac{\alpha_s}{8\pi}b_3$	$\frac{\alpha_s}{8\pi}b_3$
c_ψ^i	1	0

ξ is the non-minimal coupling of Higgs to Ricci scalar, i.e. $\xi R|H|^2$.

b-coefficients of the SM gauge couplings

- The SM gauge coupling beta-function coefficients b_i are defined as, $\beta_i = b_i g_i^3/(16\pi^2)$.

- We parametrize contributions to the running of gauge couplings as:

$$b_i = b_i^{\text{IR}} + b_i^{\text{UV}}$$

where $i = 3, 2, Y$ correspond to the $SU(3)$, $SU(2)$ and $U(1)_Y$.

- In this talk, I will focus on
  - A case which includes no contribution from UV physics to gauge beta functions, such that $b_i^{UV} = 0$ and $b_i = b_i^{IR}$, therefore

$$b_3 = -7, \quad b_2 = -19/6, \quad b_Y = 41/6.$$

Dilaton portal to dark sector

- The dilaton can provide a natural portal to dark sectors.
  [Bai et al.,0909.1319] [Agashe et al.,0912.3070] [Blum et al.,1410.1873]
- We assume the scale invariance is non-linearly realized in the dark sector.
- The dilaton couple to mass/gauge kinetic terms of the dark sector fields.
- We consider the case where dark matter (DM) is the gauge boson of a dark $U(1)_X$ gauge symmetry.

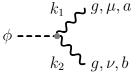
DM and dilaton portal

$$\mathcal{L}_{\rm eff}^{\rm dark} = \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{1}{2} m_X^2 X_\mu X^\mu + \frac{\phi_0}{f} \left[c_X m_X^2 X_\mu X^\mu + \frac{\alpha_X}{8\pi} b_X X_{\mu\nu} X^{\mu\nu} \right]$$

- We take $c_X = 1$ for bRS and $c_X = 0$ for anomalous case, and $\alpha_X = \dfrac{g_X^2}{4\pi}$.
  For later use, we define $\tilde{c}_X = \dfrac{\alpha_X}{8\pi} b_X$.

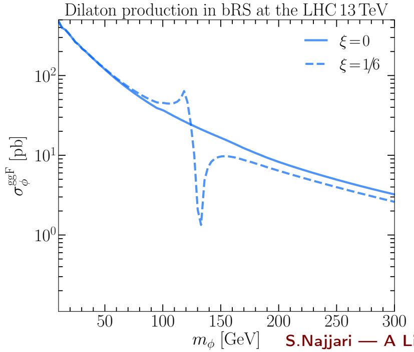
Dilaton Production Cross Section in bRS

- In the following, we consider the dilaton mass $m_\phi \in [10-300]$ GeV.
- The main production channel of the dilaton at the LHC is the ggF.



$$i\delta^{ab}\frac{\alpha_s}{4\pi v}\Big[\left(b_3+\tfrac{2}{\alpha_s kR}+\tfrac{4}{3}\right)\tilde{g}_\phi+\tfrac{4}{3}g_\phi\Big]\left(\eta^{\mu\nu}k_1\cdot k_2-k_1^\nu k_2^\mu\right)$$

where $\quad g_\phi = \sin\theta + 6\xi\frac{v}{f}\frac{\cos\theta}{Z}, \qquad \tilde{g}_\phi = \frac{v}{f}\frac{\cos\theta}{Z}, \qquad Z^2 \equiv 1 + 6\xi(1-6\xi)\frac{v^2}{f^2}$



Dilaton searches at the LHC

- One of the main motivation to consider the phenomenology of a light dilaton in mass range $m_\phi \in [10-300]$ GeV is that this includes challenging region for various LHC searches which are at present not strongly constrained.

- In the following, we note that this mass range can be classified in three sub-divisions based on the experiment data.

$$R_1 = [10 \sim 60] \text{ GeV}, \quad R_2 = [60 \sim 160] \text{ GeV}, \quad R_3 = [160 \sim 300] \text{ GeV}.$$

- R_1 covers mass range below $m_h/2$ where LHC has very limited searches and the LEP bounds would become very important.

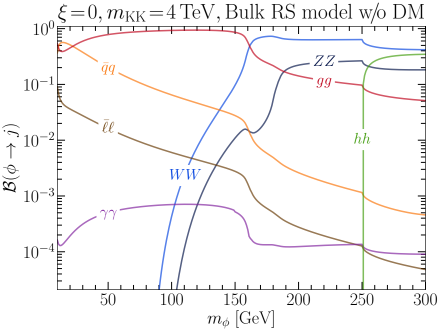
- This is the mass range where LHC can improve their searches.

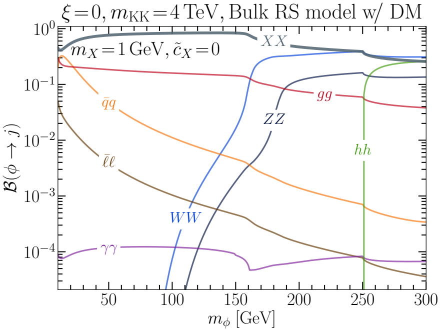
- The mass range R_2 is between $m_h/2$ and $2m_W$, and it is relatively much better covered at the LHC.

- For dilaton masses above $2m_W$, i.e. R_3, the LHC puts stringent constraints due to di-boson searches.

Branching Ratio of Dilaton in bRS

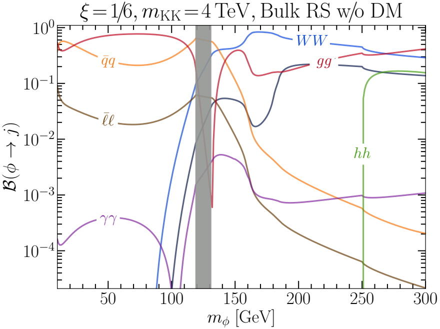
- The branching fractions of the dilaton in the bulk RS for $\xi = 0$, without (left) and with (right) DM.

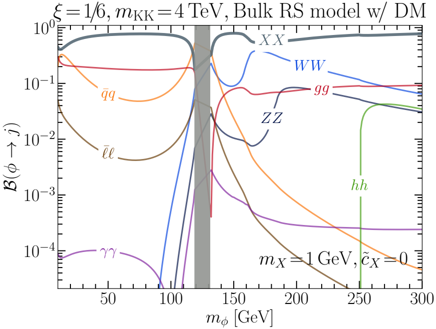




Branching Ratio of Dilaton in bRS

- The branching fractions of the dilaton in the bulk RS for $\xi = 1/6$, without (left) and with (right) DM.



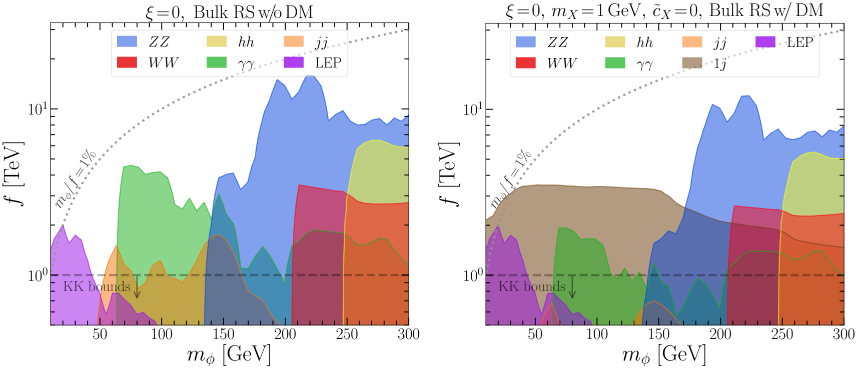


Exclusion bounds on dilaton in the bulk RS

- The parameter space of the dilaton in the bRS for $\xi = 0$, without (left) and with (right) DM.
- The scale f is the related to the KK masses ($m_{\rm KK}^{\rm LHC} \gtrsim 3$ TeV) as:

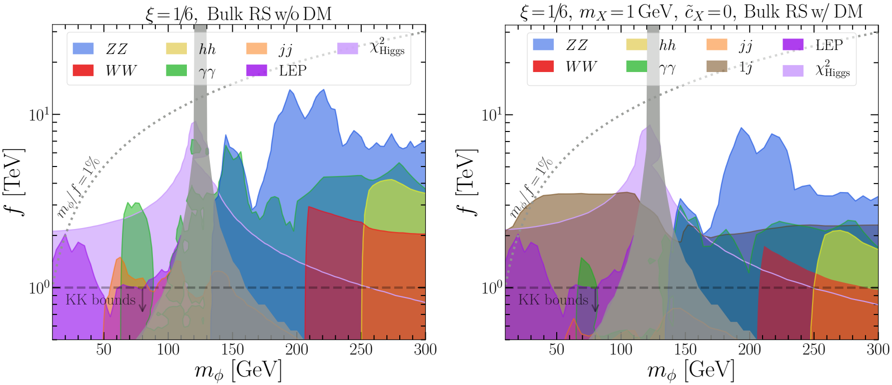
[CMS,1803.06292] [ATLAS,1804.10823] [Agashe et al.,0701186]

$$f = \sqrt{\frac{3}{2}}\frac{M_{\rm Pl}}{k} m_{\rm KK}, \qquad k/M_{\rm Pl} \lesssim 3 \text{ [Naive Dimensional Analysis]}$$



Exclusion bounds on dilaton in the bulk RS

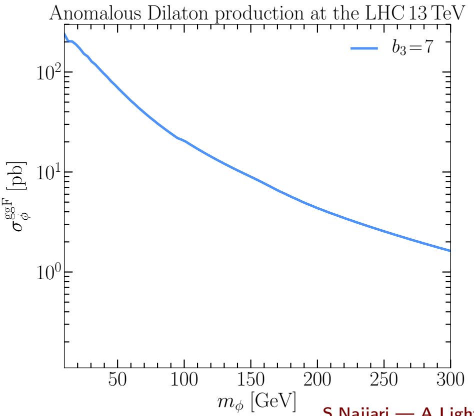
- The parameter space of the dilaton in the bulk RS for $\xi = 1/6$, without (left) and with (right) DM.



Dilaton Anomalous Production Cross Section

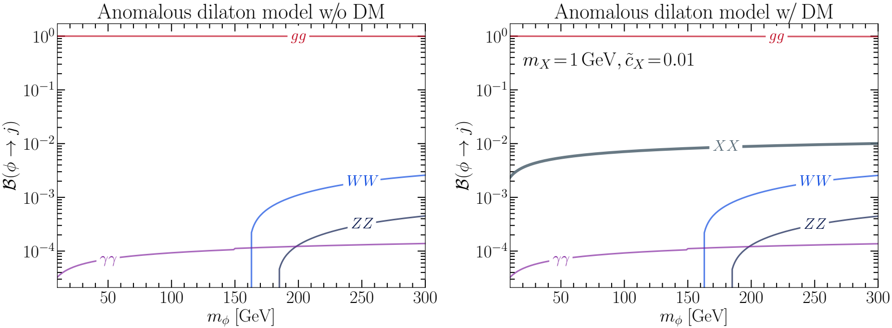
- The main production channel of the anomalous dilaton at the LHC is the ggF, where its coupling is:

$$g_{\phi gg} = \frac{\phi}{f}\frac{\alpha_s}{8\pi} b_3 G^a_{\mu\nu} G^{a,\mu\nu}$$



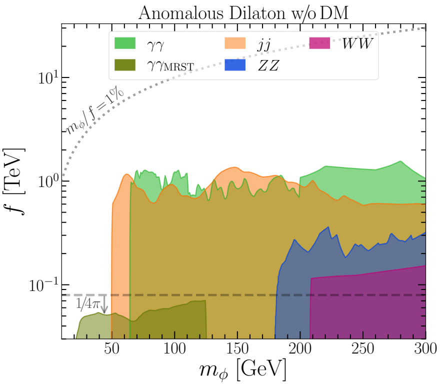
Branching Ratio of Dilaton in Anomalous model

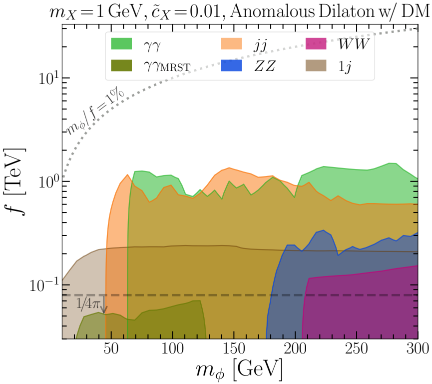
- The branching fractions of the dilaton in the anomalous dilaton model, without (left) and with (right) DM.



Exclusion bounds on the anomalous dilaton

- The parameter space of the dilaton in the anomalous scenario, without (left) and with (right) DM.
- If the mass scale $\Lambda = 4\pi f$, associated with the breaking of scale invariance is above 1 TeV, then $f \gtrsim 1/(4\pi)$.





Conclusions

- If BSM physics respects (approximate) scale/conformal invariance, the lightest observable state at the LHC may only be the dilaton.
- We explored a relatively light dilaton mass window at the LHC in two scenarios; bulk RS and anomalous dilaton.
- Dilaton can provide a natural portal to dark sectors.
- We consider a vector DM via the dilaton portal and looked for its signatures at the LHC in the mono-jet searches.
- The parameter space of these models are explored at the LHC incorporating all the current experimental data.