Holographic Techni-dilaton

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Outline

- Introduction: Higgs particle, dilaton, and technicolor.
- Gauge/gravity dualities: can techni-dilaton mass be small? Top-down holographic approach suggests: yes.
- Gauge/gravity dualities: can dilaton couplings resemble Higgs particle ones? Bottom-up holographic approach suggests: yes, but they can be distinguished.
- LHC searches: where do we stand?
- Conclusions

Higgs particle as a Dilaton

MINIMAL STANDARD MODEL

- Gauge bosons kinetic terms

$$\mathcal{L}_1 = -\frac{1}{2}\mathrm{Tr}F_{\mu\nu}F^{\mu\nu} + \cdots ,$$

- Fermions kinetic terms

$$\mathcal{L}_{1/2} = \bar{\psi}\, i\not{D}\, \psi + \cdots ,$$

- Scalar kinetic term

$$\mathcal{L}_0 = (D_\mu H)^\dagger D^\mu H$$

- Yukawa couplings

$$\mathcal{L}_y = -y\, \bar{\psi}_L\, H\, \psi_R + \cdots ,$$

- Scalar potential

$$\mathcal{L} = -\mathcal{V} = -\mu^2 H^\dagger H - \lambda \left(H^\dagger H\right)^2 .$$

Minimization

- Vacuum Expectation Value (VEV)

$$\langle H^\dagger H\rangle = -\frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2} ,$$

- Physical Higgs mass

$$H = \frac{v+h}{\sqrt{2}} \to m_h^2 = -2\mu^2 = 2\lambda v^2 .$$

Classical scaling dimensions

- Action

$$\mathcal{S} = \int \mathrm{d}^4x\, \mathcal{L} \to [\mathcal{L}] = [x]^{-4}$$

- Bosons

$$[A_\mu] = [x]^{-1} \to [F_{\mu\nu}] = [\partial_\mu A_\nu] = [x]^{-2} ,$$
$$[H] = [x]^{-1} \to [D_\mu H] = [\partial_\mu H] = [x]^{-2} ,$$

- Fermions

$$[\psi] = [x]^{-3/2} \to [D_\mu\psi] = [\partial_\mu\psi] = [x]^{-5/2} ,$$

Conformal Symmetry Breaking

- **Explicit**: the μ^2 term is the **ONLY** term in the Lagrangian that breaks dilatation symmetry at the classical level.
- **Spontaneous**: the VEV v^2 breaks the symmetry in the vacuum.
- **Higgs as a Dilaton**: taking the limit $\lambda \to 0$ ($\mu^2 \to 0$) while keeping v^2 fixed, implies $m_h^2 \to 0$. The Higgs is the dilaton, the pseudo-Goldstone boson associated with global scaling invariance.

Higgs Particle Couplings

- At classical level the SM Higgs is a (pseudo-)dilaton.
- Coupling to stress-energy tensor yields coupling via the masses:

$$\begin{aligned}\mathcal{L} = \; & 2\frac{h}{v}\, m_W^2\, W^{\mu +} W_\mu^- \\ & + \frac{h}{v}\, m_Z^2\, Z^\mu Z_\mu \\ & - \frac{h}{v}\, m_\psi\, \bar{\psi}\psi \cdots \end{aligned}$$

- Huge predictive power: the phenomenology is completely determined by symmetry principles. Only one parameter (the explicit symmetry breaking parameter, i.e. the mass of the Higgs particle).
- Deviations come from quantum effects (coupling to gluons and photons...) and/or from suppressed higher-order operators (new physics at TeV scale...).
- General question: in your favorite extension of the Standard Model, is there a dilaton? If so, it will look very similar to a light Higgs!
- Specific question: is there a light dilaton in walking TC? We will see that this is at least possible.

TECHNICOLOR

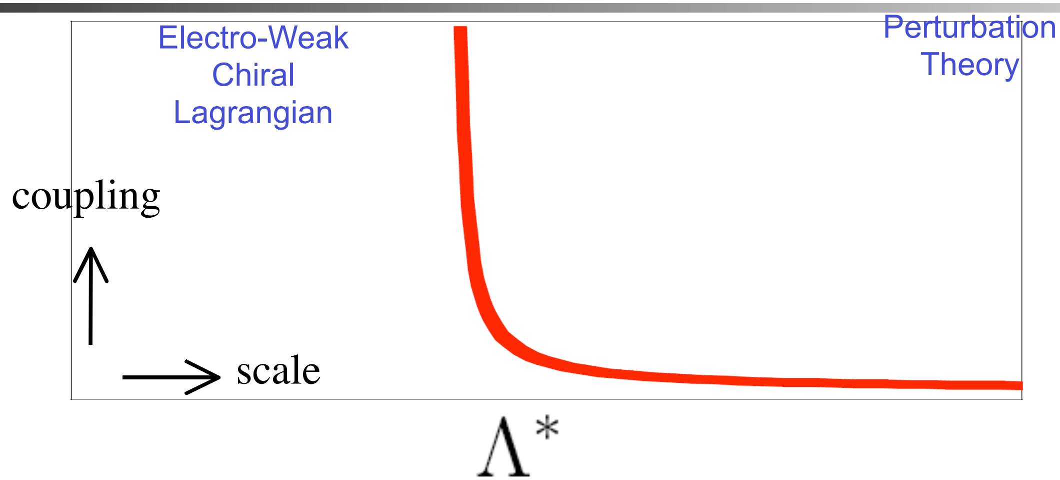
- Instead of weakly coupled sector responsible for EWSB (Higgs field), introduce a new strongly-coupled sector responsible for EWSB.
- Question 1: calculating at strong coupling?
- Question 2: models with QCD-like dynamics already ruled out (by precision measurements...). But most importantly: what does this imply?

- Answer 2: dynamics MUST be very different from QCD. Walking TC candidate.

- Question 3: is there or not a light scalar? (in QCD, we know there is not, but what about walking TC?)
- Question 4: how do you tell the difference?
- Question 5: what did LHC discover?

- Answer 1: try holography!

QCD-like Technicolor.



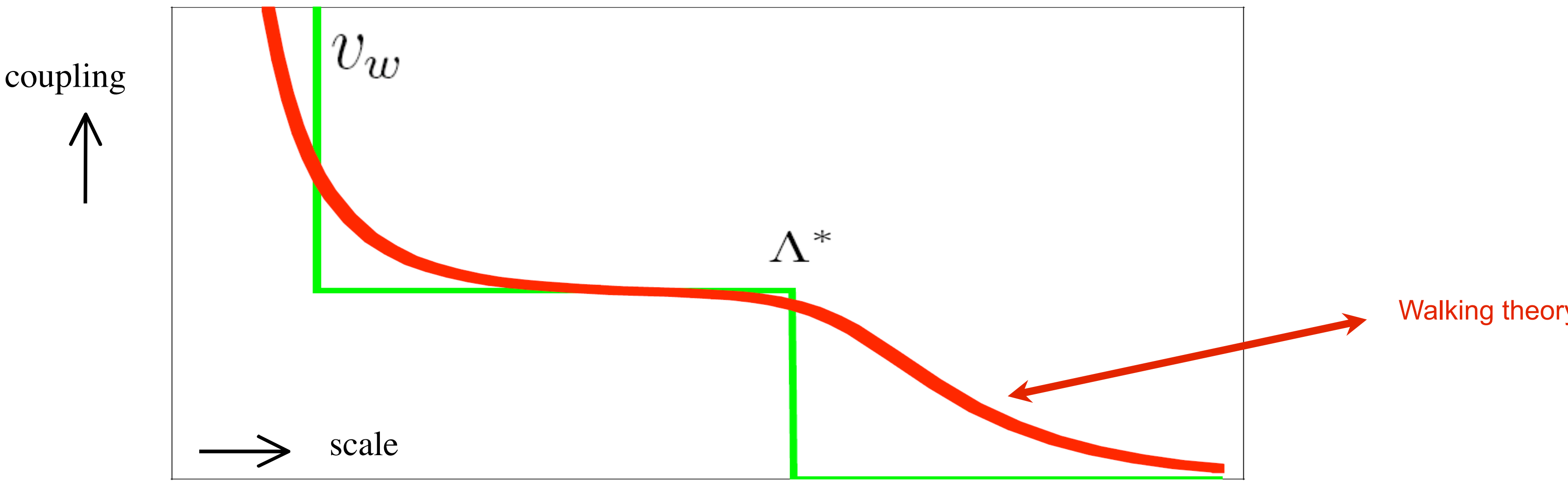
Traditional Technicolor, QCD-like. ONE dynamical scale:

NO big hierarchy problem (CFT at weak coupling), but

- Computational problem: strong coupling.
- Phenomenological problem(s): one only scale and no small parameters, and hence, even if you do not know how to compute precisely, expect problems with precision physics, FCNC, fermion masses, light pseudo-scalars ... THIS IDEA WAS RULED OUT IN THE 90ies!

WALKING TC

Holdom 1985, Yamawaki et al. 1986, Appelquist et al. 1986



- Strong dynamics, very different from QCD: approximate scale invariance, large anomalous dimensions, long intermediate energy range...
- Multi-scale dynamics: NDA expectations changed, large hierarchies introduce small parameters.
- Phenomenology can be accommodated!

- Computing?
- Is there a light scalar (dilaton)? In field theory, not known!

W. A. Bardeen *et al.* Phys. Rev. Lett. 56, 1230 (1986); M. Bando *et al.* Phys. Lett. B 178, 308 (1986); Phys. Rev. Lett. 56, 1335 (1986); B. Holdom and J. Terning, Phys. Lett. B 187, 357 (1987); Phys. Lett. B 200, 338 (1988); D. D. Dietrich, F. Sannino and K. Tuominen, Phys. Rev. D 72, 055001 (2005) [arXiv:hep-ph/0505059]. T. Appelquist and Y. Bai, arXiv:1006.4375 [hep-ph]; K. Haba, S. Matsuzaki, K. Yamawaki, Phys. Rev. D82, 055007 (2010). [arXiv:1006.2526 [hepph]]; L. Vecchi, [arXiv:1007.4573 [hep-ph]]; M. Hashimoto, K. Yamawaki, Phys. Rev. D83, 015008 (2011). [arXiv:1009.5482[hep-ph]].

SM Higgs vs. Walking-TC dilaton.

- Generic dilaton model: leading-order analysis.
- Three parameters: decay constant, coupling to photons and to gluons.

MSM Higgs h	Dilaton d
$2\frac{h}{v_W}M_W^2 W_\mu W^\mu$	$2a\frac{d}{v_W}M_W^2 W_\mu W^\mu$
$\frac{h}{v_W}M_Z^2 Z_\mu Z^\mu$	$a\frac{d}{v_W}M_Z^2 Z_\mu Z^\mu$
$-\frac{h}{v_W}M_\psi \bar{\psi}\psi$	$-a\frac{d}{v_W}M_\psi \bar{\psi}\psi$
$\frac{1}{4}\beta_e\frac{h}{v_W}F_{\mu\nu}F^{\mu\nu}$	$\frac{1}{4}c_\gamma a\beta_e\frac{d}{v_W}F_{\mu\nu}F^{\mu\nu}$
$\frac{1}{2}\beta_s\frac{h}{v_W}\mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu}$	$\frac{1}{2}c_g a\beta_s\frac{d}{v_W}\mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu}$

- Notice: only leading-order, and fermion treatment simplified.
- Production and decay mechanism modified.

SM Higgs vs. Walking-TC dilaton.

- Production:

$$\begin{aligned}
\sigma(pp \to d)_{7,8} &= a^2\, c_g^2\, \sigma(pp \to h)_{7,8}^{SM}\,, \\
\sigma(pp \to qqd)_{7,8} &= a^2\, \sigma(pp \to qqh)_{7,8}^{SM}\,, \\
\sigma(pp \to Vd)_{7,8} &= a^2\, \sigma(pp \to Vh)_{7,8}^{SM}\,, \\
\sigma(pp \to ttd)_{7,8} &= a^2\, \sigma(pp \to tth)_{7,8}^{SM}\,.
\end{aligned}$$

- Decay:

$$\rho \equiv \frac{1}{0.913 + 0.0022\, c_\gamma^2 + 0.085\, c_g^2}$$

$$\begin{aligned}
BR(d \to b\bar{b}) &= \rho\, BR(h \to b\bar{b})_{SM}\,, \\
BR(d \to c\bar{c}) &= \rho\, BR(h \to c\bar{c})_{SM}\,, \\
BR(d \to \tau^+\tau^-) &= \rho\, BR(h \to \tau^+\tau^-)_{SM}\,, \\
BR(d \to ZZ^*) &= \rho\, BR(h \to ZZ^*)_{SM}\,, \\
BR(d \to WW^*) &= \rho\, BR(h \to WW^*)_{SM}\,, \\
BR(d \to \gamma\gamma) &= c_\gamma^2\, \rho\, BR(h \to \gamma\gamma)_{SM}\,, \\
BR(d \to gg) &= c_g^2\, \rho\, BR(h \to gg)_{SM}\,.
\end{aligned}$$

Dilaton Mass

- Very difficult QFT open question. No general consensus. But very plausible light techni-dilaton in walking TC: approximate scale invariance and condensates (spontaneous breaking).
- Open question: which effect dominates, between explicit and spontaneous breaking of scale invariance?
- Gauge/gravity dualities: is it POSSIBLE that the techni-dilaton be light? What types of models would this identify?
- Problem: severe model-dependence, and very hard technical work at model-building level needed.
- Advantage: precise prescription for the calculations exists! Instead of a strongly-coupled field theory, write the model as a weakly-coupled gravity theory in extra-dimensions.

Dilaton Mass

- Bottom-up approach advantages: easy and flexible model-building, calculation of masses easy, basic phenomenology easy.
- Bottom-up approach disadvantages: not a fundamental theory (nor a systematic EFT), unrealistic description of confinement. Results on dilaton mass model-dependent.

- Top-down advantages: derived from fundamental string theory model (very rigid structure), confinement admits sensible description. Dilaton mass computed reliably.
- Top-down disadvantages: model-building very challenging, computing mass spectrum very hard (one example done!), phenomenology hard.

- Complementarity of the two.

Top-down approach (consistent truncation)

- Start from 10D superstring theory (Type IIB for example), consider supergravity limit.
- Write a general ansatz: internal 5D compact manifold with given symmetries, non-compact 5D.
- Perform KK reduction to 5D (obtain infinite number of 5D states, discrete spectrum).
- Choose subgroup of symmetries, and perform consistent truncation (keep only few 5D states).

- Write sigma-model with n scalars coupled to 5D gravity.
- Solve bulk equations for scalars and gravity, and identify physical meaning of integration constants.
- Fix background of interest (=choose and fix integration constants).

- Add boundaries in UV and IR, as regulators, and infer appropriate boundary conditions.
- Fluctuate 5D scalars and gravity.
- Rewrite fluctuations in gauge-invariant form and focus on physical degrees of freedom.
- Solve for scalar fluctuations and mass spectrum.
- Remove regulators (if possible), and obtain physical quantities of dual field theory.

- Lift to 10-dimensions.
- Study extended objects, probe strings (confinement), probe D-branes (chiral symmetry breaking)...

Bottom-up approach

- Write sigma-model with n scalars coupled to 5D gravity.
- Solve bulk equations for scalars and gravity, and identify physical meaning of integration constants.
- Fix background of interest.

- Add boundaries in UV and IR, as regulators, and infer appropriate boundary conditions.
- Fluctuate 5D scalars and gravity.
- Rewrite fluctuations in gauge-invariant form and focus on physical degrees of freedom.
- Solve for scalar fluctuations and mass spectrum.
- Remove regulators (possible in UV, NOT in IR).

5D sigma-models (consistent truncation)

- Given a background, one can study the spectrum of scalar fluctuations (systematic algorithmic procedure exists!), using gauge-invariant variables:

$$\mathfrak{a}^a = \varphi^a - \frac{\bar{\Phi}'^a}{6A'}h,$$
$$\mathfrak{b} = \nu - \frac{\partial_r(h/A')}{6},$$
$$\mathfrak{c} = e^{-2A}\partial_\mu\nu^\mu - \frac{e^{-2A}\Box h}{6A'} - \frac{1}{2}\partial_r H,$$
$$\mathfrak{d}^\mu = e^{-2A}\Pi^\mu{}_\nu\nu^\nu - \partial_r\epsilon^\mu,$$
$$\mathfrak{e}^\mu{}_\nu = h^{TT\mu}{}_\nu.$$

Berg, Haack, Mueck hep-th/0507285

- Bulk equations and boundary terms known in general:

$$\left[\mathcal{D}_r^2 + 4A'\mathcal{D}_r + e^{-2A}\Box\right]\mathfrak{a}^a - \left[V^a{}_{|c} - \mathcal{R}^a{}_{bcd}\bar{\Phi}'^b\bar{\Phi}'^d + \frac{4(\bar{\Phi}'^a V_c + V^a\bar{\Phi}'_c)}{3A'} + \frac{16V\bar{\Phi}'^a\bar{\Phi}'_c}{9A'^2}\right]\mathfrak{a}^c = 0,$$

$$\left[\delta^a{}_b + e^{2A}\Box^{-1}\left(V^a - 4A'\Phi'^a - \lambda^a{}_{|c}\bar{\Phi}'^c\right)\frac{2\bar{\Phi}'_b}{3A'}\right]\mathcal{D}_r\mathfrak{a}^b\Big|_{r_i} =$$
$$\left[\lambda^a{}_{|b} + \frac{2\bar{\Phi}'^a\bar{\Phi}'_b}{3A'} + e^{2A}\Box^{-1}\frac{2}{3A'}\left(V^a - 4A'\bar{\Phi}'^a - \lambda^a{}_{|c}\bar{\Phi}'^c\right)\left(\frac{4V\bar{\Phi}'_b}{3A'} + V_b\right)\right]\mathfrak{a}^b\Big|_{r_i}$$

D. Elander, MP, arXiv:1010.1964

- Procedure: take your (confining) background, introduce UV and IR cutoffs (regulators), solve bulk equations and apply boundary conditions, repeat by progressively removing the two cutoffs. If IR and UV are healthy, the cutoff effects will decouple.

Dilaton Mass

- Bottom-up approach: many examples exist in the literature, we build new ones which resemble more string-inspired models. Light dilaton persists. (five examples)

- Top-down approach: very hard model-building problem, challenging technical problems to compute spectrum. We did find one example were such light dilaton exists. (example N. 6)

Dilaton Mass

- Example 1: Randall-Sundrum 1.
- AdS space, two boundaries (IR and UV).
- Dilaton is present in the spectrum (good).
- It is exactly massless (bad for phenomenology).
- Confinement by hand (hard-wall)

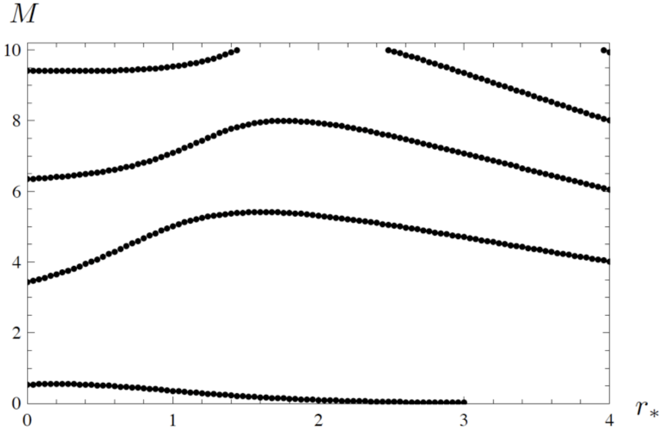
- Example 2: Goldberger-Wise.
- Add one bulk scalar to the RS1 set-up, with quadratic (super-)potential.
- Dilaton acquires finite mass, parametrically small provided the scalar is dual to a VEV ($\Delta>2$), or to a quasi-marginal deformation ($\Delta\cong 0$).
- Mass is UV-cutoff dependent (bad).
- Confinement by hand (hard-wall)

Dilaton Mass

- Example 3: cubic superpotential.
- Kink solution for the bulk scalar, models the flow between fixed points:

$$\bar{\Phi} = \frac{\Phi_I}{1 + e^{\Delta(r - r_*)}}$$

- Similar models exist in the stringy context (see Pilch-Warner).
- Light dilaton present, finite mass independent of UV cutoff (good).



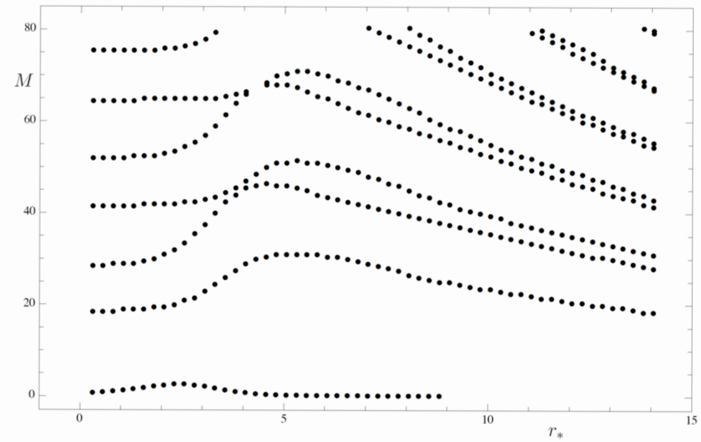
- Dependence on crude IR cutoff modeling still there (bad).

Dilaton Mass

- Example 4: Pilch-Warner 2-scalar system, more complicated dynamics (dual to flow to Leigh-Strassler fixed point):

$$W = \frac{e^{-2\alpha}}{4}\left[\cosh(2\chi)\left(e^{6\alpha}-2\right)-\left(3e^{6\alpha}+2\right)\right]$$

- Solution still a kink. Spectrum contains light scalar:



- Notice: calculations are much harder and more rigorous, but results are very similar to Model 3.

Dilaton Mass

- Example 5: GPPZ (and its truncations or generalizations).
- No IR cut-off, end-of-space emerges dynamically from non-trivial superpotential:

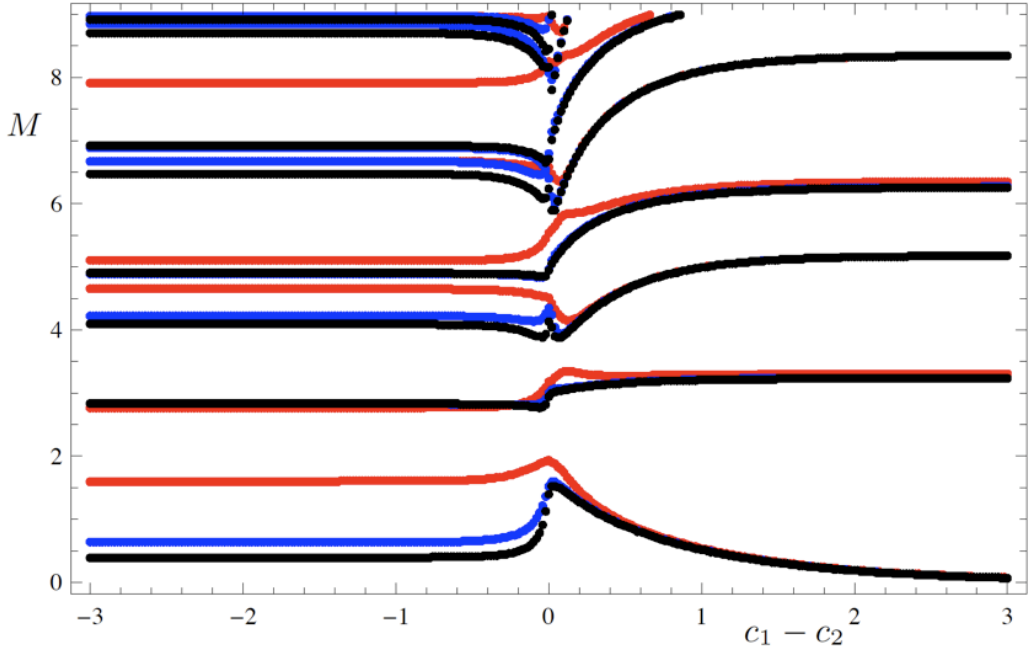
$$W = -\frac{3}{4}\left(\cosh 2\sigma + \cosh\frac{2m}{\sqrt{3}}\right)$$

- Singular behavior of the five-dimensional theory in the IR, while UV is asymptotically AdS:

$$\begin{aligned}
\sigma &= \operatorname{arctanh}\left(e^{-3r+3c_1}\right) \simeq e^{3c_1}\xi^3\,,\\
m &= \sqrt{3}\operatorname{arctanh}\left(e^{-r+c_2}\right) \simeq \sqrt{3}e^{c_2}\xi\,,\\
e^{2A} &= e^{-2r}\left(-1+e^{6(r-c_1)}\right)^{1/3}\left(-1+e^{2(r-c_2)}\right)e^{2c_1+2c_2} \simeq e^{2r}\,,
\end{aligned}$$

- Dilaton present, and mass is finite and UV-independent, PROVIDED the singularity is controlled by the Δ=3 VEV.

Dilaton Mass



- A light dilaton is present in the right part of the plot (Δ=3 dominates),
- Spurious state is NOT a dilaton in the left half (Δ=1 dominates),
- 10D lift known, this is a full stringy model. Unfortunately, badly singular: no Wilson loop (confining potential) can be computed.

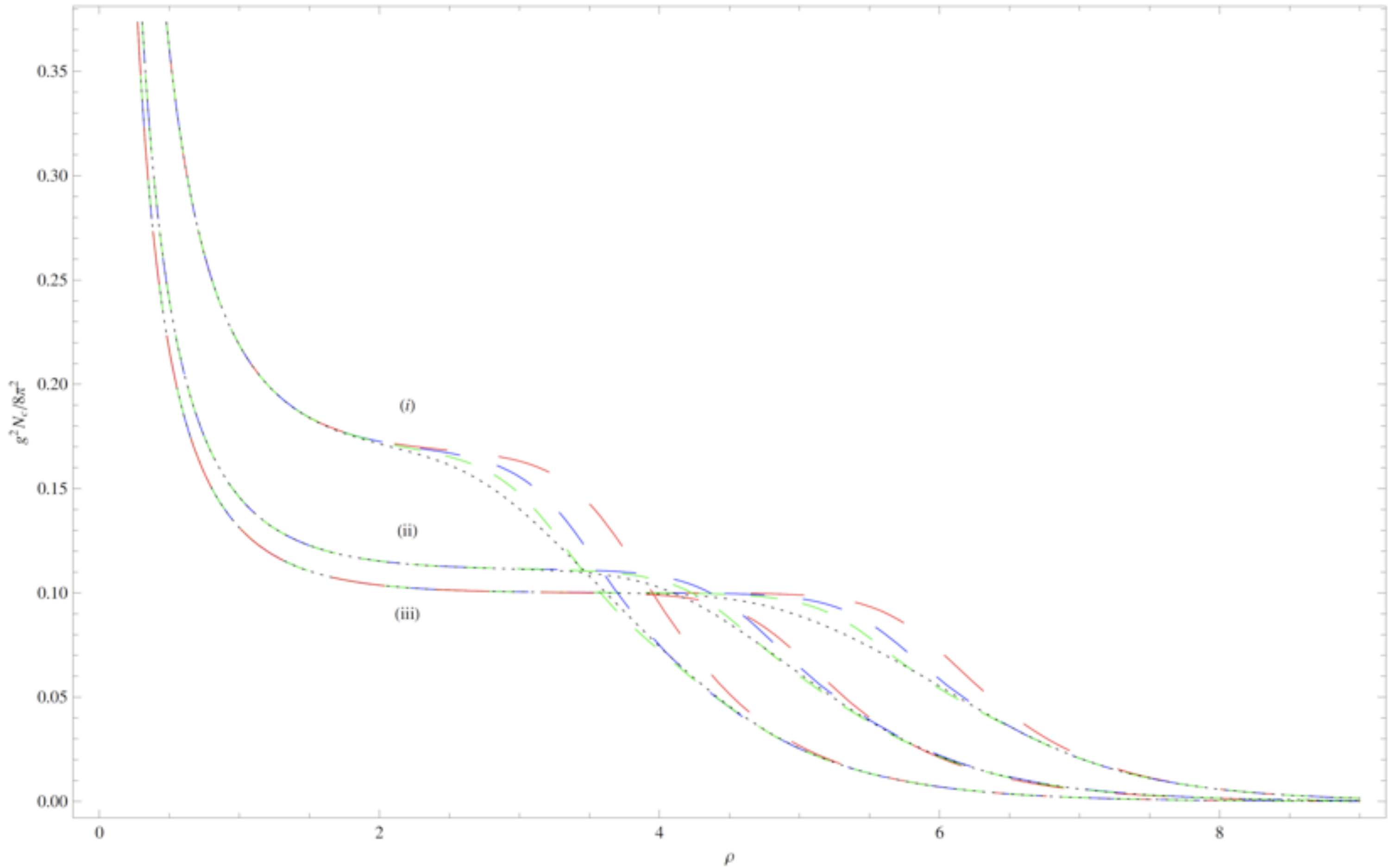
Dilaton Mass

- Example 6: walking backgrounds from conifold and deformations.
- Very rich type-IIB class of models, many solutions.
- 5D consistent truncation(s) known but complicated (PT):

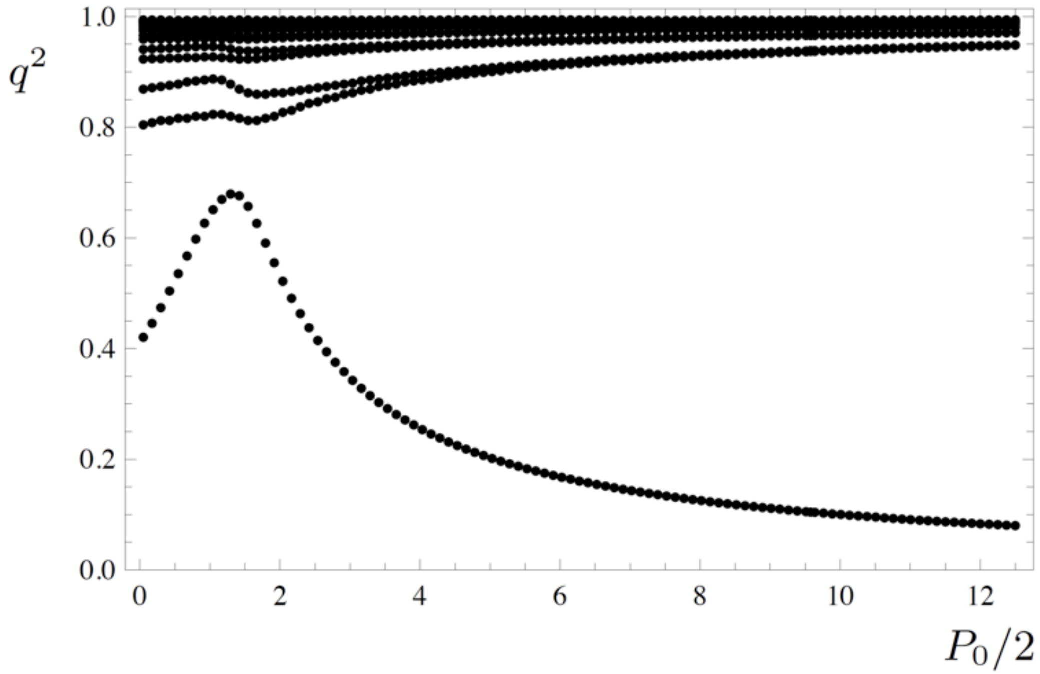
$$
\begin{aligned}
V \;=\; & -\frac{1}{2}e^{2p-2x}(e^{\tilde{g}}+(1+a^2)e^{-g})+\frac{1}{8}e^{-4p-4x}(e^{2\tilde{g}}+(a^2-1)^2e^{-2\tilde{g}}+2a^2) \\
& +\frac{1}{4}a^2e^{-2\tilde{g}+8p}+\frac{1}{8}N^2e^{\Phi-2x+8p}\left[e^{2\tilde{g}}+e^{-2\tilde{g}}(a^2-2ab+1)^2+2(a-b)^2\right] \\
& +\frac{1}{4}e^{-\Phi-2x+8p}h_2^2+\frac{1}{8}e^{8p-4x}(M+2N(h_1+bh_2))^2\,.
\end{aligned}
$$

- Walking behavior seen in classes of solutions.
- Walking region NOT AdS: hyperscaling violation.
- UV asymptotic NOT AdS: computing couplings challenging.
- Light dilaton is present in the spectrum.
- Well behaved 10D sugra: Wilson loop can be computed, yields linear confining potential from quark-antiquark test particles.

Walking Dynamics from String Dual



Scalar Mass Spectrum



- A light dilaton emerges when the walking region is long.
- Notice: confinement dynamical feature (Wilson loop can be computed).
- Only known example with such light scalar from top-down!

Dilaton Mass: Summary

- Starting from RS1, the feature of a light dilaton seems to persist in the spectrum in much more realistic and refined holographic models.
- Technical difficulties grow substantially towards full 10-d supergravity. In particular, computing the couplings becomes very hard with many scalars and non-AdS asymptotics.
- A confining, non-singular, asymptotically-AdS supergravity background admitting a light dilaton has not been found yet. But we are very close.
- A class of top-down models in which a light composite scalar is present exists: proof of existence of light dilaton in strongly-coupled dynamics.

Dilaton Mass: take-home message

- A LIGHT SCALAR PARTICLE IS PRESENT IN LARGE CLASSES OF STRONGLY-COUPLED MODELS, AND ITS COUPLINGS ARE QUALITATIVELY SIMILAR TO THOSE OF THE HIGGS BOSON (BECAUSE BOTH ARE DILATONS)!

Phenomenology

- Bottom-up approach: many models exist.
- S-parameter computed in many ways and for many variants.
- Generic result consistent with EFT expectations: mass of techni-rho meson must be large, M>2.5-3 TeV.
- Decay constant of dilaton F computed in many ways and for many variants.
- Generic results in stringy units:

$$\frac{M_\rho}{\Lambda_0} \simeq 2.5 - 3\,,$$
$$\frac{F}{\Lambda_0} \simeq 1.2\,,$$

- Reinstating physical units implies F>1.1 TeV (a ~ 0.22).

- Top-down approach: much less is known! Work in progress...

Implications and comments

- The calculation of the decay constant of the holographic techni-dilaton yields model-independent and large result in bottom-up models with approximately AdS geometry. Why? Is this true also in top-down? Open questions.

- The coupling of the dilaton to all SM particles is suppressed, in particular VBF, Vh and tth production at the LHC is going to be suppressed (small parameter a). However, coupling to photons and gluons can be enhanced by large-N effects.

- Possible counter-examples? No calculation exists of the decay constant for string-theory models (top-down) having non-AdS geometry (work in progress...).

LHC

- Scalar particle with mass 125-126 GeV found.
- Decay to ZZ established (CMS agrees with SM, ATLAS a bit high)
- Decay to 2 photons established (CMS agrees with SM, ATLAS a bit high).
- Decay to WW established (but lower significance)
- Decay to 2 tau seen (but lower significance)

- Decay to two b? (CMS sees it, ATLAS does not, TeVatron uncertain)
- Production mechanism other than ggF (VBF and Vh in particular) not clearly established yet.

- The simplest explanation is that this is the elementary Higgs boson of the SM, but too early to rule out other possibilities (such as dilaton).

Summary and open questions

- (Holographic techni-)dilaton as well as SM Higgs compatible with data.
- Photon-photon enhancement would favor techni-dilaton.
- VBF, Vh and tth suppression would favor techni-dilaton (if bottom-up holographic results trusted).

- Phenomenology of consistent models from top-down holography unknown (yet). But there exists example with light scalar particle.

- More experimental data and more theoretical work on top-down approach needed in order to establish the elementary/composite nature of the Higgs particle discovered at the LHC.