The naturally light dilaton

or

How to break dilations spontaneously and naturally

Riccardo Rattazzi (EPFL)

in collaboration with R. Contino and A. Pomarol

Mass Hierarchies and scale invariance

$\sim$ scale invariant dynamics

(conformal invariance)

✦ Under what conditions is the breaking of scale invariance spontaneous?

✦ Should we expect the associated Goldstone boson?

Goldberger, Grinstein, Skiba 07

General framework

- scale invariant QFT $\quad \mathcal{O}(x) \longrightarrow e^{d_{\mathcal{O}} t}\mathcal{O}(e^t x)$

- spontaneously broken dilations $\quad \langle \mathcal{O}(x) \rangle = M^{d_{\mathcal{O}}} \neq 0$

- Goldstone boson $\quad t \to \varphi(x) \quad \equiv$ dilaton

- dilations $\quad D \; : \quad \varphi(x) \to \varphi'(x) \equiv \varphi(kx) + \log k$

- special conformal $\quad K_\mu \; : \quad \varphi(x) \to \varphi'(x) \equiv \varphi\big(x + (c\,x^2 - 2(c\cdot x)x)\big) - 2c_\mu x^\mu$

One Goldstone suffices to parametrize $\quad O(4,2)/Iso(3,1)$

ordinary Goldstone $\varphi(x) \to \varphi(x) + c$ $V(\varphi) = 0$

dilaton $\varphi(x) \to \varphi(kx) + \ln k$ $V(\varphi) = V_0\, e^{4\varphi}$

canonical dilaton $\chi \equiv f_D\, e^{\varphi}$ $V_0 \propto f_D^4$

Pattern of SO(4,2) breaking controlled by V_0

Fubini '76

$V_0 = 0$	$\langle \chi \rangle = f_D = \text{const}$	ISO(3,1) Poincaré-4
$V_0 > 0$	$\langle \chi \rangle \propto \frac{1}{z}$	SO(3,2) AdS4
$V_0 < 0$	$\langle \chi \rangle \propto \frac{1}{t}$	SO(4,1) dS4

generically (without SUSY) spontaneous SO(4,2) ➓ ISO(3,1) not realized

Parenthesis

Sundrum '03

$$\partial^2 \chi = \lambda \chi^3$$

$$\lambda = \frac{V_0}{f_D^4}$$

$V_0 = 0$	$\langle \chi \rangle = f_D = \mathrm{const}$	Poincaré-4
$V_0 > 0$	$\langle \chi \rangle \propto \frac{1}{z}$	AdS4
$V_0 < 0$	$\langle \chi \rangle \propto \frac{1}{t}$	dS4

$$\chi^2 \quad \sim \quad g_{\mu\nu} = \chi^2 \eta_{\mu\nu}$$

light dilaton problem $\sim$ small cosmological constant problem ordinary Goldstone $\varphi(x) \to \varphi(x) + c$ $V(\varphi) = 0$

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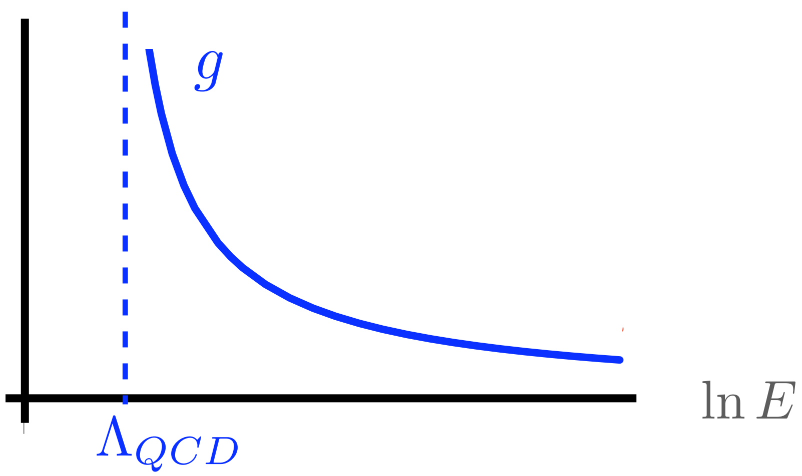
Enters explicit breaking of conformal invariance

$$\Delta\mathcal{L} = g\mathcal{O} \qquad\qquad \mu\frac{d}{d\mu}g \neq 0$$

A) QCD like: no dilaton

$$m_D \sim \Gamma_D \sim \Lambda_{QCD}$$



$$\mathcal{L}_{eff} \quad = N^2\left[(\partial\chi)^2 + \chi^4 F(\Lambda/\chi) + \ldots\right]$$

★ large N ?

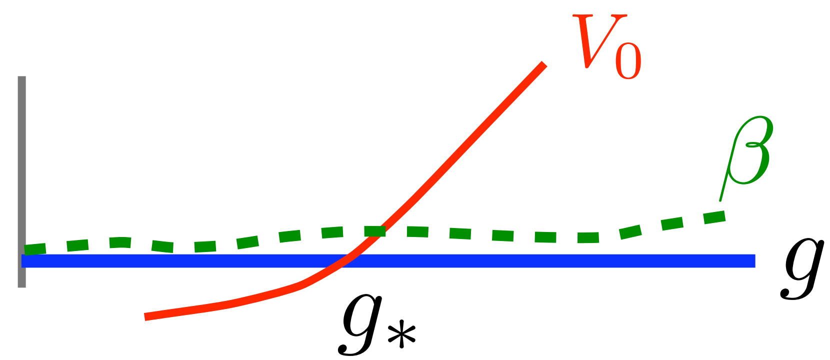
Holdom, Terning '86

B) naturally light dilaton

- imagine g exactly marginal over finite range: *manifold of fixed points*

- $V(\varphi) = e^{4\varphi}\, V_0(g)$

- generically ∃ $V_0(g_*) = 0$



- imagine g acquires small dimension β over whole marginality surface

$$\mu \frac{d}{d\mu} g = \beta(g) = O(\epsilon)$$

- scale invariance $V \to e^{4\varphi} V_0\left(g(e^{\varphi})\right) \equiv \chi^4 V_0\left(g(\chi)\right)$ $f_D = 1$

- relaxation mechanism $g(e^{\varphi}) \longrightarrow g_*$ at minimum

$$m_\varphi^2 \simeq 4 f_D^2 V_0'(g_*)\beta(g_*) = O(\epsilon)$$

- ✦ Slow running of effective coupling allows vacuum to relax close to zero of dilaton quartic V_0 whatever “initial” value of V_0
- ✦ pseudo-Dilaton seems “naturally” light
- ✦ it was crucial to assume $\beta(g) \ll 1$; which seems more like a very special dynamical assumption
- ✦ to better judge we need an explicit example

Dual realization of light dilaton in Randall-Sundrum

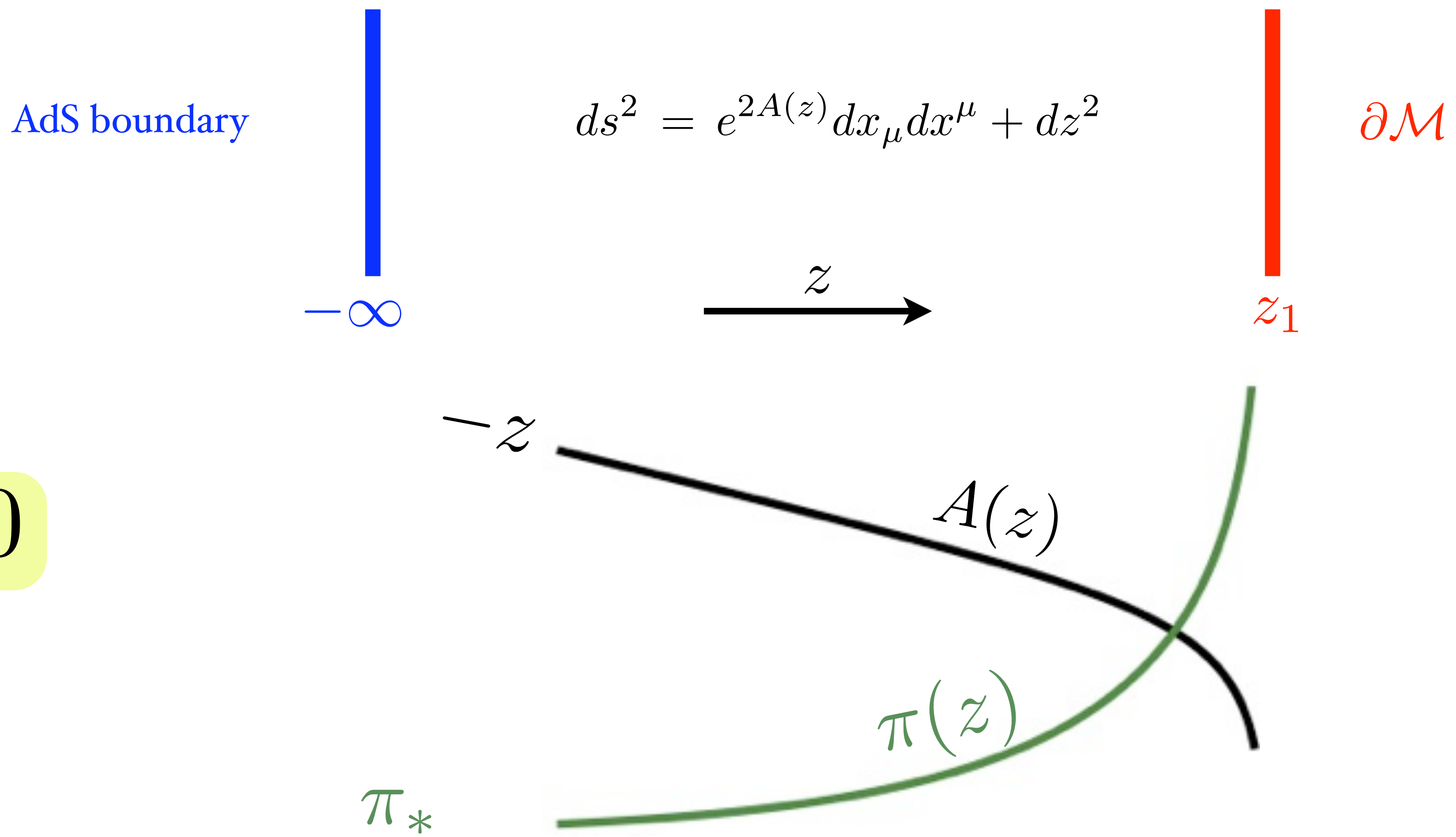
Golberger, Wise '99
Arkani-Hamed, Porrati, Randall '00
Rattazzi, Zaffaroni '00

	CFT4		AdS5	
	dilaton	$\longleftrightarrow$	radion	
marginal	g	$\longleftrightarrow$	π	bulk Goldstone boson
near marginal	$\beta(g) \ll 1$	$\longleftrightarrow$	π	bulk pseudo-Goldstone boson
	$V_0(g)$	$\longleftrightarrow$	$\tau(\pi)$	IR brane tension

5D realization

$L_{AdS} = 1$

$$S/M_5^3 = \int_{\mathcal{M}} \sqrt{g}\left[\frac{1}{4}R - \frac{1}{2}(\partial\pi)^2 + \frac{1}{3} - \epsilon P(\pi)\right] - \int_{\partial\mathcal{M}} \sqrt{g_{ind}}\,\tau(\pi)$$



$\epsilon = 0$

π_* = number fixed by $\tau(\pi)$ ⟺ g_* tuned coupling

z_1 = free parameter ⟺ $-z_1(x) = \varphi(x)$ massless dilaton

$\epsilon \neq 0$

$$\frac{d\pi}{dz} = -\frac{\epsilon}{4} P'(\pi) \equiv \beta(\pi)$$

RG evolution of dual coupling

Ex : $P = \frac{\pi^2}{2}$ $\qquad \lim_{z\to-\infty} \pi(z) = e^{\frac{\epsilon}{4}(z-z_1)}\, \pi_* \left[1 + O(\epsilon)\right]$

- asymptotic behaviour, no longer fixed: no tuning
- conversely: asymptotic behaviour fixes z_1

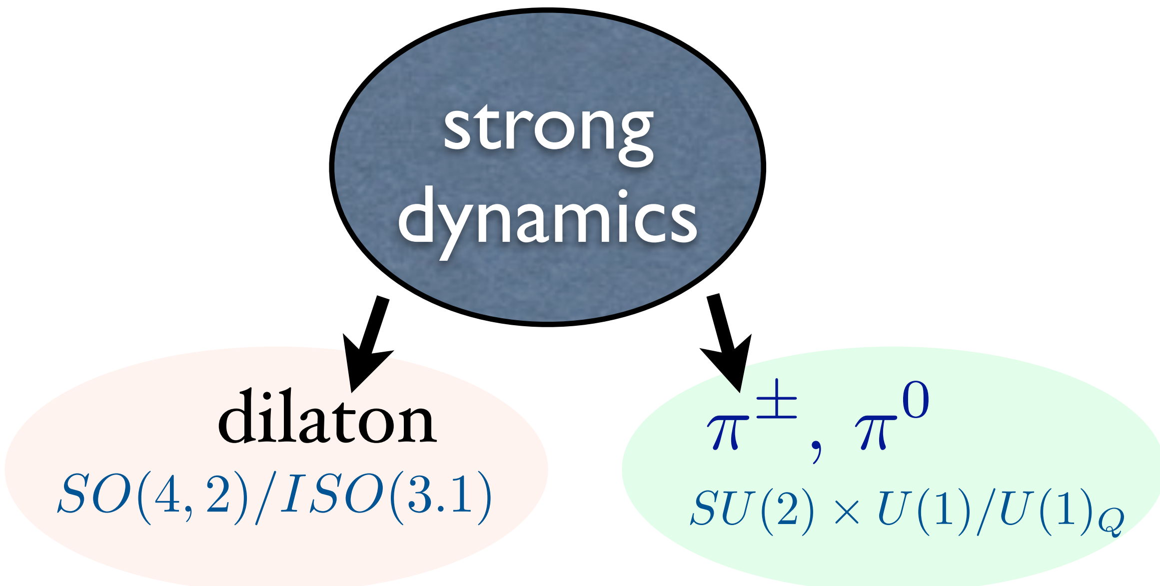
for arbitrary RG flow $\pi(z)$ dilaton ground state is at $\pi(z_1) \simeq \pi_*$

- KK-spectrum modified by O(ϵ) effects: $m_\varphi^2 \propto \tau'(\pi(z_1))\beta(\pi_*) = O(\epsilon)$
- dilaton always has positive kinetic term
- RS model with light dilaton realized dynamically without the slightest tuning of IR brane tension

Impersonators of the SM Higgs boson

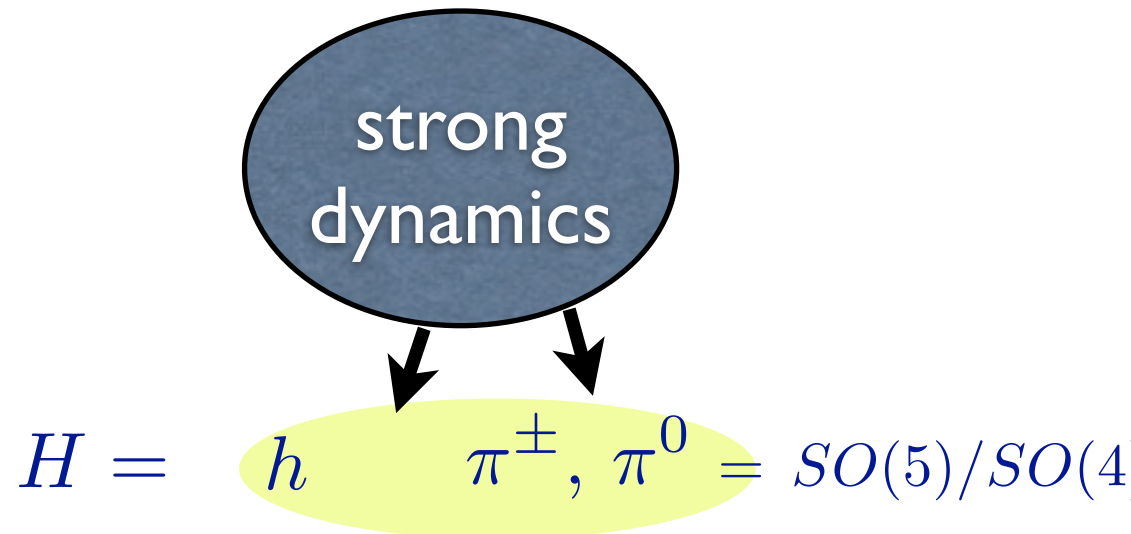
Georgi, Kaplan '84
....
Agashe, Contino, Pomarol '04

Higgsless with Light dilaton



Goldberger, Grinstein, Skiba 07

Pseudo-Goldstone Higgs doublet



Giudice, Grojean, Pomarol, Rattazzi 07

Low energy phenomenology of impersonators constrained by non-linearly realized symmetry and by the structure of its explicit breaking (selection rules)

General parametrization of *Higgs impersonator h*

Contino, Grojean, Moretti, Piccinini, RR '10

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{M_V^2}{2}\mathrm{Tr}\left(V_\mu V^\mu\right)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \dots\right] - m_i \bar{\psi}_{Li}\left(1 + c\frac{h}{v}\right)\psi_{Ri} + \text{h.c.}$$

$$+ \frac{1}{2}m_h^2 h^2 + d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \dots$$

$$+ c_g \frac{\alpha_s}{4\pi}\frac{h}{v}G_{\mu\nu}G^{\mu\nu} + c_\gamma \frac{\alpha}{4\pi}\frac{h}{v}F_{\mu\nu}F^{\mu\nu}$$

c flavor universal in minimal flavor violating set up

✦ Standard Model: $a = b = c = d_3 = 1$ $\qquad c_g = c_\gamma = 0$

$\mathcal{A}(VV \to VV) \simeq \frac{s}{v^2}(1 - a^2)$ $\qquad \mathcal{A}(VV \to hh) \simeq \frac{s}{v^2}(b - a^2)$ $\qquad \mathcal{A}(VV \to \psi\bar{\psi}) \simeq \frac{m_\psi \sqrt{s}}{v^2}(1 - ac)$

$SO(5)/SO(4)$ Pseudo-Goldstone Higgs

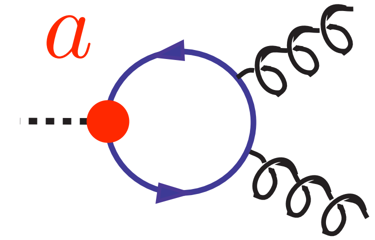
Agashe, Contino, Pomarol '04

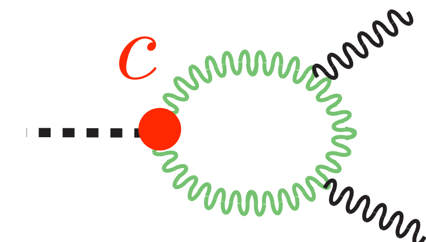
3 parameters

$a = \sqrt{1 - v^2/f^2}$ $\quad b = 1 - 2v^2/f^2$ model independent

$c,\ d_3 = 1 + O(v^2/f^2)$ model dependent

$c_g,\ c_\gamma \sim \dfrac{\alpha_t}{4\pi}$ controlled by small explicit SO(5) breaking
NEGLIGIBLE!





Deviations in Higgs production and decay controlled by a and c

$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)|_{SM}} = \frac{\Gamma(h \to f\bar{f})}{\Gamma(h \to f\bar{f})|_{SM}} = c^2 \qquad \frac{\Gamma(h \to VV)}{\Gamma(h \to VV)|_{SM}} = a^2$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)|_{SM}} = a^2 \left[1 + R(1 - c/a)\right]^2 \sim a^2 \qquad R \sim 0.22 \div 0.28$$

LHC with 300 fb^{-1} sensitive to 10-40% effects
In principle pseudo-Goldstone hypothesis can be tested by suitable ratios of rates

$$\left[\frac{\sigma(gg\to h)\mathrm{Br}(h\to VV)}{\sigma(VV\to h)\mathrm{Br}(h\to VV)}\right] = \left(\frac{c}{a}\right)^2 \left[\frac{\sigma(gg\to h)\mathrm{Br}(h\to VV)}{\sigma(VV\to h)\mathrm{Br}(h\to VV)}\right]_{SM}$$

$$\left[\frac{\sigma(gg\to h)\mathrm{Br}(h\to \gamma\gamma)}{\sigma(gg\to h)\mathrm{Br}(h\to VV)}\right] = (1+R(1-c/a))^2 \left[\frac{\sigma(gg\to h)\mathrm{Br}(h\to \gamma\gamma)}{\sigma(gg\to h)\mathrm{Br}(h\to VV)}\right]_{SM}$$

$$\left(\frac{c}{a}\right)^2 \simeq 1\pm 0.5 \quad \longrightarrow \quad (1+R(1-c/a))^2 \simeq 1\pm 0.15$$

visible
with 30 fb^{-1}

barely visible
with 300 fb^{-1}

Duhrssen 03
Lafaye, Plehn, Rauch, Zerwas, Duhrssen 09

Large deviations in both channels would rule out Goldstone hypothesis

Dilaton case

Goldberger, Grinstein, Skiba '07
Vecchi '10

3 parameters

$$\begin{cases} a = \sqrt{b} = c = \dfrac{v}{f_D} \\ d_3 = \dfrac{5}{3}\dfrac{v}{f_D} + O(\epsilon) \\ c_g,\, c_\gamma = O(v/f_D) \end{cases}$$

$$a,\, b,\, c \lessgtr 1$$

$$\frac{\Gamma(h \to VV)}{\Gamma(h \to f\bar{f})} = \frac{\Gamma(h \to VV)|_{SM}}{\Gamma(h \to f\bar{f})|_{SM}}$$

$$\frac{\Gamma(h \to VV)}{\Gamma(h \to \gamma\gamma)} \Big/ \frac{\Gamma(h \to VV)|_{SM}}{\Gamma(h \to \gamma\gamma)|_{SM}} = a^2/(1 + \# c_\gamma)^2 \not\approx 1$$

different pattern
than pseudo-Goldstone

Ex.

$$\left[\frac{\sigma(VV \to h)\mathrm{Br}(h \to \bar{\tau}\tau)}{\sigma(VV \to h)\mathrm{Br}(h \to VV)}\right] = \left[\frac{\sigma(VV \to h)\mathrm{Br}(h \to \bar{\tau}\tau)}{\sigma(VV \to h)\mathrm{Br}(h \to VV)}\right]_{SM}$$

Large deviations in this channel would rule out dilaton hypothesis

Summary

✦ Conformal symmetry alone does not forbid a dilaton potential

✦ Under special (but natural) dynamical assumptions, explicitly broken conformal invariance provides a relaxation mechanism for the dilaton mass

✦ What about the cosmological constant problem?

✦ Introduce 3-form field $A_{\mu\nu\rho}$ $\qquad F = d \wedge A$

eq. of motion: $F = \text{const}$ $\qquad \Lambda \to \Lambda(F)$ fixed by boundary conditions

can we "enrich" the dynamics of F to make it flow sometime or somewhere towards F_* such that $\Lambda(F_*) = 0$