Higgslike dilatons

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**Discovery of 126 GeV Higgs**

- A new particle at ~ 126 GeV that behaves very similarly to SM Higgs
Discovery of 126 GeV Higgs

- Couplings compatible with SM values, but at this point could also be quite off.
Higgsless
Pure MSSM
Higgs sector
• Do we really have to completely do away with strong EWSB?

• Couplings of Higgs in SM: determined by approximate conformal symmetry of SM

• In absence of Higgs mass parameter SM approximately conformal until QCD scale, and \( <H> = v \) breaks conformality spontaneously

• Higgs = dilaton, with \( f = v \), Higgs couplings determined a la Shifman, Vainshtein, Voloshin, Zakharov ’79-’80
• Can have a higgs-like dilaton in more complicated models of dynamical EWSB

• Need strong sector to be approximately conformal

• Conformality should be broken spontaneously at scale $f \sim v$

• Aim here:
  • Examine what it takes for dilaton to be light $<< \Lambda$
  • SUSY, RS examples
  • Examine if dilaton couplings can fit LHC data
Dilaton basics

• Scale transformations
  \[ x \rightarrow x' = e^{-\alpha x} \]

• Operators transform
  \[ \mathcal{O}(x) \rightarrow \mathcal{O}'(x) = e^{\alpha \Delta} \mathcal{O}(e^\alpha x) \]

• \( \Delta \) is full dimension, classical plus quantum corrections

• Change in action:
  \[ S = \sum_i \int d^4x \ g_i \mathcal{O}_i(x) \rightarrow S' = \sum_i \int d^4x \ e^{\alpha (\Delta_i - 4)} g_i \mathcal{O}_i(x) \]

• Assume spontaneous breaking of scale inv. (SBSI)
  \[ \langle \mathcal{O} \rangle = f^n \]
Dilaton basics

• Dilaton: Goldstone of SBSI, \( \sigma \), transforms non-linearly under scale transf.: 
\[
\sigma(x) \rightarrow \sigma(e^\alpha x) + \alpha f
\]

• Restore scale invariance by replacing VEV 
\[
f \rightarrow f \chi \equiv f e^{\sigma/f}
\]

• Effective dilaton Lagrangian is then (using NDA for coeffs)
\[
\mathcal{L}_{\text{eff}} = \sum_{n,m \geq 0} \frac{a_{n,m}}{(4\pi)^{2(n-1)} f^{2(n-2)} \chi^{2n+m-4}} \frac{\partial^{2n} \chi^m}{\chi^{2n+m-4}}
\]
\[
= -a_{0,0} (4\pi)^2 f^4 \chi^4 + \frac{f^2}{2} (\partial_\mu \chi)^2 + \frac{a_{2,4}}{(4\pi)^2} \frac{(\partial \chi)^4}{\chi^4} + \ldots
\]
Dilaton dynamics

- **Main point of dilaton:** effective action can have non-derivative $\chi^4$ term - just the cosmological constant in the composite sector

$$ S = \int d^4 x \frac{f^2}{2} (\partial \chi)^2 - a f^4 \chi^4 + \text{higher derivatives} $$

- Generically $a \neq 0$. Will make SBSI difficult:
  - $a > 0$: VEV at $f=0$, no SBSI
  - $a < 0$: runaway vacuum $f \rightarrow \infty$
  - $a = 0$ arbitrary $f$

- Need to add additional almost-marginal operator to generate dilaton potential
Dilaton dynamics

• Perturbation:

\[ \delta S = \int d^4 x \lambda(\mu) \mathcal{O} \]

\[ af^4 \rightarrow f^4 F(\lambda(f)) \]

• Dilaton potential:

\[ V(\chi) = f^4 F(\lambda(f)) \text{ vacuum energy in units of } f \]

• To have a VEV:

\[ V' = f^3 [4F(\lambda(f)) + \beta F'(\lambda(f))] = 0 \]

\[ \beta = \frac{d\lambda}{d \log \mu} \]

• Dilaton mass:

\[ m_{dil}^2 = f^2 \beta [\beta F'' + 4F' + \beta' F'] \approx 4f^2 \beta F'(\lambda(f)) = -16f^2 F(\lambda(f)) \]
Dilaton dynamics

- We need $m_{dil} \sim 125\text{ GeV}$

- With $f \sim v = 246\text{ GeV}$, $\Lambda = 4\pi f \sim 3\text{ TeV}$

- So $m_{dil} \sim f/2 \ll \Lambda$

- But dilaton mass:

  $$m_{dil}^2 = f^2 \beta [\beta F'' + 4F' + \beta' F'] \approx 4f^2 \beta F'(\lambda(f)) = -16f^2 F(\lambda(f))$$

- Naive expectation: one loop vacuum energy

  $$F_{NDA} \sim \frac{\Lambda^4}{16\pi^2 f^4} \sim 16\pi^2$$

  $$m_{dil} \sim \Lambda$$
Dilaton dynamics

• Generically **DO NOT** expect a light dilaton, need the dilaton quartic to be suppressed vs. NDA size

• If quartic **not** suppressed, need **large** $\beta$ to stabilize, **large explicit** breaking a la QCD and TC, **no light** dilaton

• Need to start with an **almost flat** direction

• Dynamics should not generate a large contribution to the vacuum energy...

• **Natural** in SUSY theories - have flat or almost flat directions

• Not natural in non-SUSY theories
Dilaton dynamics

To find a (non-SUSY) solution we need

• Small vacuum energy (tuning), $a \ll 16\pi^2$

• $\delta F$ dynamically cancels vs. $a$

• Perturbation should be close to marginal
Dilaton dynamics

• Detailed examination of the dynamics

• Assume small deviation $\epsilon$ from marginality, and coupling $\lambda$:

$$\beta(\lambda) = \frac{d\lambda}{d \ln \mu} = \epsilon \lambda + \frac{b_1}{4\pi} \lambda^2 + O(\lambda^3)$$

• Assume $\lambda$ perturbative $\lambda<4\pi$, and dilaton quartic very small

$$F(\lambda) = (4\pi)^2 \left[ c_0 + \sum_n c_n \left( \frac{\lambda}{4\pi} \right)^n \right], \quad c_0 \ll c_n \sim 1, \quad a = (4\pi)^2 c_0$$

• Coleman-Weinberg type potential for dilaton
Dilaton dynamics

• For perturbative $\lambda$ can introduce large hierarchies

$$f \sim M \left( \frac{-4\pi c_0}{\lambda(M)c_1} \right)^{1/\varepsilon}$$

if $\varepsilon$ small and negative $f<<M$ (if positive more tuning)

• The dilaton mass:

$$\frac{m_{dil}^2}{\Lambda^2} \sim \frac{\beta}{\pi} \sim \frac{\lambda}{\pi}$$

• Could make it very small by taking $\varepsilon\rightarrow0$?
**Dilaton dynamics**

• When $\epsilon$ very small, $\lambda^2$ term in $\beta$-function dominates

$$\frac{m^2_{dil}}{\Lambda^2} \sim \frac{\beta}{\pi} \sim \frac{\lambda^2}{4\pi^2}$$

• Shows need perturbative coupling for light dilaton

• QCD and (walking)-TC will not have a light dilaton, since there $\lambda=\tilde{g} \sim 4\pi$

• Fine-tuning in weakly coupled models: min. condition gives

$$\lambda(f) \sim 4\pi c_0/c_1 \equiv 4\pi/\Delta \quad \text{where } \Delta \text{ is FT}$$

$$\Delta \gtrsim 2\Lambda/m_{dil} \simeq 50 \left( \frac{f}{246\text{GeV}} \right) \left( \frac{125\text{GeV}}{m_{dil}} \right)$$
A SUSY example for a light dilaton

- Look at 3-2 model

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- Classical flat directions $Q\bar{D}L$, $Q\bar{U}L$ and $\det(Q\bar{Q})$

- Lifted by superpotential $W = \lambda Q\bar{D}L$

- Dynamical ADS superpotential $W_{\text{dyn}} = \frac{\Lambda_3^7}{\det(Q\bar{Q})}$

- Will push fields to large VEVs $>>\Lambda_3$ as long as $\lambda<<1$

- Spontaneous conformality breaking, expect light dilaton
A SUSY example for a light dilaton

- The potential \( V \approx \frac{\Lambda_3^{14}}{f^{10}} + \lambda \frac{\Lambda_3^7}{f^3} + \lambda^2 f^4 \)

- VEVs: \( f \approx \frac{\Lambda_3}{\lambda^{1/7}} \), \( V \approx \lambda^{10/7} \Lambda_3^4 \)

- Dilaton mass: \( m_{\text{dil}} \approx \lambda f \approx \lambda^{6/7} \Lambda_3 \)

- Of course here SUSY is playing the essential role of keeping the dilaton light, unlike in the non-SUSY examples we are interested in
The radion in RS/GW

- The effective potential w/o stabilization

\[ V_{eff} = V_0 + V_1 \left( \frac{R}{R'} \right)^4 + \Lambda_5 R \left( 1 - \left( \frac{R}{R'} \right)^4 \right) \]

- With f=1/R’ get a characteristic SBSI potential with quartic

\[ V_{eff}(\chi) = V_0 + \Lambda_5 R + f^4 \left( V_1 R^4 - \Lambda_5 R^5 \right) \]

CC, FT1 \quad quartic, FT2

- Natural size of quartic: NDA in 5D like in 4D EFT

\[ \delta a_{bulk} \sim \Lambda_5 R^5 \sim \frac{12\frac{5}{2}}{24\pi^3} \sim O(1) \]

\[ \delta a_{IR} = -V_1 R^4 = -V_1 \left( \frac{R}{R'} \right)^4 R'^4 = \frac{\tilde{V}_1}{\left( \frac{\Lambda}{4\pi} \right)^4} \sim 16\pi^2 \]
The radion in RS/GW

• Assumption for GW: quartic is set to zero/very small, then bulk scalar added with non-trivial profile and small bulk mass

• Potential:

\[ V = f^4 \left\{ (4 + 2\epsilon) \left[ v_1 - v_0 (fR)^\epsilon \right]^2 - \epsilon v_1^2 + \delta a + O(\epsilon^2) \right\} = f^4 F(f) \]

• \( \epsilon \) is bulk mass, \( v_{1,0} \) IR/UV VEVs in units of AdS curvature, \( \delta a \) the remaining quartic

• VEV:

\[ f = \frac{1}{R} \left( \frac{v_1 + \sqrt{-\delta a/4}}{v_0} + O(\epsilon) \right)^{1/\epsilon} \]

• Tuning determined by \( \sqrt{-\delta a/4} \lesssim v_1 \)

• Amount:

\[ \Delta = \frac{a}{|\delta a|} \gtrsim \frac{4\pi^2}{v_1^2} \sim 4000 \text{ for } v_1 \sim 0.1. \]
Radion as Higgs?

- Radion kinetic term normalization gives
  \[ f^{(RS)} = \frac{1}{R'} \sqrt{12(M_* R)^3} \]

- For calculability need \( N = \sqrt{12(M_* R)^3} \gg 1 \), so

- For higgsless:
  \[ \frac{v}{f^{(RS)}} = \frac{2}{g \sqrt{\log \frac{R'}{R}}} \]

- For models with very heavy higgs:
  \[ \frac{v}{f^{(RS)}} = \frac{v R'}{N} \]

- Both cases couplings very suppressed, but mass light
  \[ m_{dil} \sim M_{KK} \frac{2v_1 \sqrt{\epsilon}}{\sqrt{12(M_* R)^3}} \]
Dilaton couplings

• **Assumption**: composite sector + elementary sector

• **Composite** sector close to conformal, breaks scale inv. spontaneously

• **Elementary** sector is external to composite, but weak couplings

• **Dilaton coupling in composite sector**: assume in UV

\[
L_{CFT}^{UV} = \sum_i g_i \mathcal{O}_i^{UV}
\]

• **All operators dim 4 or small explicit breaking**  
  \[ [g_i] = 4 - \Delta_i^{UV} \]

• **Generic IR Lagrangian**  
  \[
  L_{CFT}^{IR} = \sum_i c_j (\prod g_i^{n_i}) \mathcal{O}_j^{IR} \chi^{m_j}
  \]
Dilaton couplings I. Composites

- Power of $\chi$ fixed
  \[ \mathcal{L}_{CFT}^{IR} = \sum_i c_j \left( \Pi g_i^{n_i} \right) \mathcal{O}_j^{IR} \chi^{m_j} \]

- $m_j = 4 - \Delta_j^{IR} - \sum_i n_i (4 - \Delta_i^{UV})$

- Single coupling:
  \[ \mathcal{L}_{breaking}^{IR} = \sum_j c_j g_i \left( \Delta_i^{UV} - \Delta_j^{IR} \right) \mathcal{O}_j^{IR} \frac{\sigma}{f} \]

- If no explicit breaking
  \[ \mathcal{L}_{symmetric}^{IR} = \sum_j c_j \left( 4 - \Delta_j^{IR} \right) \mathcal{O}_j^{IR} \frac{\sigma}{f} \]

- Coupling to $\text{Tr}$ of energy-momentum tensor:
  \[ \mathcal{L}_{eff} = -\frac{\sigma}{f} \mathcal{T}_\mu^\mu \]

- Trace anomaly included, for
  \[ \mathcal{O}_j^{IR} = -\left( F_{\mu\nu} \right)^2 / (4g^2) \]

\[ 4 - \Delta_j^{IR} = 2\gamma(g) = \frac{2\beta(g)}{g} \]
Dilaton couplings II. Partially composite

- **Mixing** between composite and elementary sectors

\[ \mathcal{L}^{UV} = \mathcal{L}_{CFT}^{UV} + \mathcal{L}_{elem} + \sum_i y_i \mathcal{O}_{elem,i} \mathcal{O}_{CFT,i}^{UV} \]

- Treat \( y \) as **spurion** with dimension \( [y_i] = 4 - \Delta_{elem,i}^{UV} - \Delta_{CFT,i}^{UV} \)

- **Effective Lagrangian**

\[ \mathcal{L}_{eff} = \mathcal{L}_{CFT}^{IR} + \mathcal{L}_{elem} + \sum_j c_j y_i \mathcal{O}_{elem,i} \mathcal{O}_{CFT,j}^{IR} \chi^{m_j} + \mathcal{O}(y^2) \]

- **Power of \( \chi \):**

\[ \Delta_{elem,i}^{UV} - \Delta_{elem,i}^{IR} + \Delta_{CFT,i}^{UV} - \Delta_{CFT,j}^{IR} \]
**Example I: Partially comp. fermions**

![Diagram](image)

- **Mixing** between elementary and composite fermions:
  \[
  \mathcal{L}_{int} = y_L \psi_L \Theta_R + y_R \psi_R \Theta_L + h.c.
  \]

- **Spurion dimensions:** 
  \[
  [y_L] = 4 - \Delta_{\psi_L}^{UV} - \Delta_{\Theta_R}^{UV}, \quad [y_R] = 4 - \Delta_{\psi_R}^{UV} - \Delta_{\Theta_L}^{UV}
  \]

- **The effective fermion mass:** 
  \[
  \mathcal{L}_{eff} = - M y_L y_R \psi_L \psi_R \chi^m + h.c.
  \]

- **Coupling to dilaton:** 
  \[
  \Delta_{\Theta_L}^{UV} = 2 + c_L, \quad \Delta_{\Theta_R}^{UV} = 2 - c_R,
  \]

- **In RS language:** 
  \[
  \mathcal{L}_{eff} = - M y_L y_R \psi_L \psi_R \chi^{c_L - c_R}
  \]
Example II: Partially comp. gauge field

- **Mixing** between gauge field and composite current:

\[ \mathcal{L} = -\frac{1}{4g_{UV}^2} F_{\mu\nu} F^{\mu\nu} + A_\mu \mathcal{J}^\mu \]

- **Spurion dimension**: \([g_{UV}] = \Delta_A^{UV} - 1\)

- **Low energy coupling**: \(\mathcal{L}_{eff} = -\frac{1}{4g^2} F_{\mu\nu} F^{\mu\nu} \chi^m\)

- **Coupling**: \(m = 4 - 2[1 + \Delta_A^{IR}] + 2[g] = 2\left(\frac{\beta_{IR}}{g} - \frac{\beta_{UV}}{g}\right)\)
Example II: Partially comp. gauge field

• Can also find this from matching of coupling

\[
\frac{1}{g^2(\mu)} = \frac{1}{g^2(\mu_0)} - \frac{b_{UV}}{8\pi^2} \ln \frac{\mu_0}{f} - \frac{b_{IR}}{8\pi^2} \ln \frac{f}{\mu}
\]

• With replacement \( f \rightarrow fe^{\frac{\sigma}{f}} \)

• Coupling again

\[
\frac{g^2}{32\pi^2} (b_{IR} - b_{UV}) F^{\mu\nu} F_{\mu\nu} \frac{\sigma}{f}
\]
Dilaton coupling to SM

- **Couplings to massive fields:**

  \[ \delta \mathcal{L}_{mass} = \left( 2 m_W^2 W^+_\mu W^-\mu + m_Z^2 Z^2_\mu \right) \frac{\sigma}{f} - Y_\psi \frac{v}{\sqrt{2}} \psi_L \psi_R (1 + \gamma_L + \gamma_R) \frac{\sigma}{f} + h.c. \]

- **Anomalous dimensions** \( \gamma_{L,R} \) might be flavor dependent. Assume flavor symmetry to tame dilaton mediated FCNCs.

- **Coupling to massless gauge bosons:**

  \[ \delta \mathcal{L}_{kin} = \frac{g_A^2}{32 \pi^2} \left( b^{(A)}_{IR} - b^{(A)}_{UV} \right) \left( F^{(A)}_{\mu \nu} \right)^2 \frac{\sigma}{f} \]

- **Assuming photon, gluon partially composite**

  \[ - \left( b^{(3)}_{UV} + b^{(3)}_{tL} \right) \frac{\alpha_s}{8 \pi} G^2_{\mu \nu} \frac{\chi}{f} - \left( b^{(EM)}_{UV} + b^{(EM)}_{W_T^\pm} + N_c b^{(EM)}_{tL} \right) \frac{\alpha}{8 \pi} A^2_{\mu \nu} \frac{\chi}{f} \]

Friday, March 15, 2013
Dilaton coupling to SM

- In terms of generic parametrization

\[ \mathcal{L}_{\text{eff}} = c_V \left( \frac{2m_W^2}{v} W^+_\mu W^-\mu + \frac{m_Z^2}{v} Z_\mu \right) h - c_t \frac{m_t}{v} tt h - c_b \frac{m_b}{v} bb h - c_\tau \frac{m_\tau}{v} \bar{\tau}\tau h + c_g \frac{\alpha_s}{8\pi v} G_{\mu\nu}^2 h + c_\gamma \frac{\alpha}{8\pi v} A_{\mu\nu}^2, \]

- For massive fields

\[ c_{t,\chi} = \frac{v}{f} (1 + \gamma_t), \quad c_{b,\chi} = \frac{v}{f} (1 + \gamma_b), \quad c_{\tau,\chi} = \frac{v}{f} (1 + \gamma_\tau), \]

- For massless GBs including top and W loops:

\[ \hat{c}_{g,\chi} \simeq \frac{v}{f} \left( b_{IR}^{(3)} - b_{UV}^{(3)} + \frac{1}{2} F_{1/2}(x_t) \right) \equiv \frac{v}{f} b_{\text{eff}}^{(3)}, \]

\[ \hat{c}_{\gamma,\chi} \simeq \frac{v}{f} \left( b_{IR}^{(EM)} - b_{UV}^{(EM)} + \frac{4}{3} F_{1/2}(x_t) - F_1(x_W) \right) \equiv \frac{v}{f} b_{\text{eff}}^{(EM)} \]
Dilaton rates and production

- **Decay rates:**
  \[
  \frac{\Gamma_{WW}}{\Gamma_{WW,SM}} \approx |c_V|^2, \quad \frac{\Gamma_{bb}}{\Gamma_{bb,SM}} \approx |c_b|^2, \quad \frac{\Gamma_{\tau\tau}}{\Gamma_{\tau\tau,SM}} \approx |c_\tau|^2
  \]
  \[
  \frac{\Gamma_{gg}}{\Gamma_{gg,SM}} \approx \frac{|\hat{c}_g|^2}{|\hat{c}_{g,SM}|^2}, \quad \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma,SM}} \approx \frac{|\hat{c}_\gamma|^2}{|\hat{c}_{\gamma,SM}|^2}
  \]

- **Production rates:**
  \[
  \frac{\sigma_{GF}}{\sigma_{GF,SM}} \approx \frac{|\hat{c}_g|^2}{|\hat{c}_{g,SM}|^2}, \quad \frac{\sigma_{VBF}}{\sigma_{VBF,SM}} \approx |c_V|^2, \quad \frac{\sigma_{Vh}}{\sigma_{Vh,SM}} \approx |c_V|^2
  \]

- **Rates for individual channels:**
  \[ R \approx (\sigma \Gamma)/(\sigma \Gamma)_{SM} \times |C_{tot}|^{-2} \]
  \[
  R_{GF,(WW,ZZ)} \approx \frac{v^2}{f^2} \frac{1}{C^2} \left( \frac{b_{eff}^{(3)}}{b_t^{(3)}} \right)^2, \quad R_{GF,\gamma\gamma} \approx \frac{v^2}{f^2} \frac{1}{C^2} \left( \frac{b_{eff}^{(3)} b_{eff}^{(EM)}}{b_t^{(3)} b_{t+W}^{(EM)}} \right)^2, \\
  R_{GF,\tau\tau} \approx \frac{v^2}{f^2} \frac{1}{C^2} \left( \frac{b_{eff}^{(3)} (1 + \gamma_\tau)}{b_t^{(3)}} \right)^2, \quad R_{VBF,\gamma\gamma} \approx \frac{v^2}{f^2} \frac{1}{C^2} \left( \frac{b_{eff}^{(EM)}}{b_{t+W}^{(EM)}} \right)^2, \\
  R_{VBF,(WW,ZZ)} \approx \frac{v^2}{f^2} \frac{1}{C^2}, \quad R_{VBF,\tau\tau} \approx \frac{v^2}{f^2} \frac{1}{C^2} (1 + \gamma_\tau)^2, \quad R_{Vh,bb} \approx \frac{v^2}{f^2} \frac{1}{C^2} (1 + \gamma_b)^2
  \]

- **where**
  \[ C = \left[ BR_{WW,SM} + BR_{ZZ,SM} + (1 + \gamma_b)BR_{bb,SM} + \frac{(b_{eff}^{(3)})^2}{(b_t^{(3)})^2} BR_{gg,SM} \right] \]
LHC and EWPT constraints

\( \gamma_i = 0 \)

\( v/f = 1, \gamma_i = 0 \)

Drive \( v/f \sim 1 \)
Enhancement in $h \rightarrow \gamma\gamma$

**Figure:** Dilaton predictions for the rates $R_{\text{incl.}}, ZZ$, green line, $R_{\text{incl.}}, \gamma\gamma$, orange line, and $R_{VH}, bb$, blue line as a function of $b_{UV}$ for $v/f = 1, \gamma_i = 0$ and $v/f = 0.8, \gamma_i = 0$.

Rates for $h \rightarrow \gamma\gamma$, $h \rightarrow ZZ$, $h \rightarrow bb$ can be easily enhanced for large $b$'s.
• Dilaton well-motivated alternative to 125 GeV higgs

• Large quartic expected for dilaton in non-SUSY models

• Hard to stabilize at hierarchically small VEVs and a light dilaton mass $<< \Lambda$, typically a tuning of a few percent - 0.01 percent involved

• Once radion light couplings predicted up to few parameters

• $v/f$ suppressed vs. Higgs, $\beta$ functions determine rest

• Can fit LHC data, and explain potential deviations from SM predictions