Higgslike Dilatons

Jay Hubisz
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Syracuse University

with: Brando Bellazzini, Csaba Csáki, Javi Serra, John Terning

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**ATLAS 2011 + 2012 Data**

\[ \int L dt \sim 4.6-4.8 \text{ fb}^{-1} \quad \text{at} \quad 7 \text{ TeV} \quad \int L dt \sim 5.8-5.9 \text{ fb}^{-1} \quad \text{at} \quad 8 \text{ TeV} \]

- Expected Combined
- Expected H → ZZ → llll
- Expected H → bb
- Observed Combined
- Observed H → ZZ → llll
- Observed H → bb
- Expected H → γγ
- Expected H → WW → llνν
- Expected H → ττ
- Observed H → γγ
- Observed H → WW → llνν
- Observed H → ττ

Local p-value

CMS

\[ \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \quad \sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1} \]

- Combined  obs.
- Exp. for SM H
- H → γγ
- H → ZZ
- H → WW
- H → ττ
- H → bb

**Discovery!**

Technicolor

Higgsless
The resonance is at $\sim 126$ GeV and it is SM-Higgs-like. Sizeable deviations still allowed.
Excited Other fermions

**Techni-hadrons (LSTC):** dilepton, m_{\chi}

**Major neutr. (LRSM, no mixing):** 2-lep + jets

**H^+ (DY prod., BR(H^+\rightarrow\mu\mu)=1):** SS dimuon, m_{H^+}

**Color octet scalar: dijet resonance, m_{\chi}

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**Extra dimensions**

- Large ED (ADD): monojet + E_{T,miss}
- Large ED (ADD): diphoton, m_{\gamma\gamma}
- UED: diphoton + E_{T,miss}
- RS1 with k/M_{Pl} = 0.1: diphoton, m_{\gamma\gamma}
- RS1 with k/M_{Pl} = 0.1: ZZ resonance, m_{ZZ}
- ADD BH (RS1 with k/M_{Pl} = 0.1): WW resonance, m_{WW}
- ADD BH (k/M_{Pl} = 0.1): tt resonance, m_{tt}
- ADD BH (M_{Pl}/M_{Pl} = 3): SS dilepton + jets + \Delta p_{T}
- Quantum black hole: dijet, F (m_{ff})
- qqq contact interaction: \langle\langle m_{qqq}\rangle\rangle
- utt CI: SS dilepton + jets + E_{T,miss}
- Z' (SM): m_{Z'}
- Z' (SM): m_{Z'}
- W (SM): m_{W}
- W (SM): m_{W}
- W (→ τg, g=1): m_{W}
- W (→ tb, SS): m_{W}
- W: m_{W}
- Scalar LQ pairs (\bar{\psi}=1): kin. var. in eejj, evjj
- Scalar LQ pairs (\bar{\psi}=1): kin. var. in u\bar{u}, d\bar{d}
- 4th generation: b\bar{b}(T_{T,3}) → WW
- Top partner: T \rightarrow t + A_{LQ} (dilepton, m_{A_{LQ}})
- Vector-like quark: CC, m_{CC}
- Vector-like quark: NC, m_{NC}
- Excited quarks: \gamma\gamma resonance, m_{\chi}
- Excited quarks: dijet resonance, m_{\chi}
- Excited electron: e-\gamma resonance, m_{\chi}
- Excited muon: \mu-\gamma resonance, m_{\chi}

**Other**

- Techni-hadrons (LSTC): dilepton, m_{\chi}
- Techni-hadrons (LSTC): WW resonance (vlll), m_{WW}
- Major neutr. (LRSM, no mixing): 2-lep + jets
- W (LRSM, no mixing): 2-lep + jets
- H^+ (DY prod., BR(H^+\rightarrow\mu\mu)=1): SS dimuon, m_{H^+}
- Color octet scalar: dijet resonance, m_{\chi}

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**ATLAS Exotics Searches - 95% CL Lower Limits (Status: LHCC, Sep 2012)**

<table>
<thead>
<tr>
<th>Process</th>
<th>m_{X} [GeV]</th>
<th>\sigma_{BR} [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z' → t\bar{t}</td>
<td>350</td>
<td>1.13</td>
</tr>
<tr>
<td>W' → τ\bar{\nu}</td>
<td>1.10</td>
<td>1.22</td>
</tr>
<tr>
<td>Z' → W\gamma</td>
<td>350</td>
<td>1.13</td>
</tr>
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</tbody>
</table>

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**Mass scale [TeV]**

- 10^{-1}
- 1
- 10
- 10^2

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**Non-discovery**

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*Only a selection of the available mass limits on new states or phenomena shown*
Non-discovery

Resonances

4th Generation

Long Lived

LeptoQuarks

Compositeness

Z'SSM ll
Z' SS M tau tau
Z', ttbar, hadronic, width=1.2%
Z', dijet
Z', ttbar, lep+jet, width=1.2%
Z'SSM ll (fbb=0.2)
G, dijet
G, ttbar, hadronic
G jet+MET k/M = 0.2
G γγ k/M = 0.1
G, Z(l)Z(qq), k/M=0.1
W' Iv
W' dijet
W' → td
W'→ WZ(leptonic)
WR' → tb
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Ball M, MD=2.1, Ms=1.7, gs=0.4
String Resonances (qg)
s8 Resonance (gg)
s8 Resonance (gg/bb), fbb=1
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
q* (qg), dijet
q* (qW)
q* (qZ)
q*, dijet pair
q*, boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
gluino, Stopped Gluino stop, HSCP
stop, Stopped Gluino stau, HSCP, GMSB
hyper-K, hyper-p=1.2 TeV
fractional charge, q=2/3e
fractional charge, q=1/3e
multiple charge, q=2e
multiple charge, q=3e
neutralino, ctau=25cm, ECAL time
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3, (bbunu) Br(LQ → bvt) = 1
LQ3, (btau) β=1.0
stop (btau)
Status of light scalars

All models seem to be under strain
Strongly coupled EWSB

- Higgsless and Technicolor models are dead
- Composite Higgs models fine tuned
- Give up on SC-EWSB?

The Higgs:

- Couplings determined by $\sim$ conformal invariance of SM (e.g. low energy theorems)
- $m_H$ is only tree-level explicit breaking
- VEV breaks conformality spontaneously
Higgs-like dilaton

- Can envision a model of strong dynamics at a conformal fixed point
- To reproduce data need conformal symmetry spontaneously broken at $f \sim v$

**Questions I will address:**

- Can a dilaton fit the data?
- Can a dilaton be light? (below $\Lambda = 4\pi f$)
Scale Transformations

Dilatations:

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

Operators transform:

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

\( \Delta \) is the full quantum operator dimension

Linearized transformation of action:

\[ S \rightarrow S + \sum_i \int d^4x \alpha g_i (\Delta_i - 4) \mathcal{O}_i(x) \]
Spontaneous breaking

CFT operator gets VEV:

\[ \langle \mathcal{O}(x) \rangle = f^\Delta \]

Corresponding goldstone boson:

\[ \sigma(x) \rightarrow \sigma(e^\alpha x) + \alpha f \]

Non-linear realization in effective theory:

\[ f \rightarrow f \chi \equiv f e^{\sigma/f} \]

Restores symmetry to LEEFT
The Dilaton Quartic

Most general terms invariant under dilatations:

\[ \mathcal{L}_{\text{eff}} = \sum_{n,m \geq 0} \frac{a_{n,m}}{(4\pi)^{2(n-1)} f^{2(n-2)}} \frac{\partial^{2n} \chi^m}{\chi^{2n+m-4}} \]

\[ = -a_{0,0} (4\pi)^2 f^4 \chi^4 + \frac{f^2}{2} (\partial_{\mu} \chi)^2 + \frac{a_{2,4}}{(4\pi)^2} \frac{(\partial \chi)^4}{\chi^4} + \ldots \]

**Large dilaton quartic**

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

**Obstruction to SBSI:**

- \( a > 0 \rightarrow f = 0 \) (no breaking)
- \( a < 0 \rightarrow f = \infty \) (runaway)
- \( a = 0 \rightarrow f = \text{anything} \) (flat direction)
Near-Marginal Deformation

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

Quartic has dependence on near marginal coupling:

\[ V(\chi) = a \chi^4 \rightarrow V = \chi^4 F(\lambda(\chi)) \]

Deformation can stabilize \( f \) away from origin

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

Expanding the potential:

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

small, so dilaton is light, right?

F is the cosmological constant in f units:

\[ F_{\text{NDA}} \approx \frac{\Lambda^4}{16\pi^2 f^4} \approx 16\pi^2 \]

Need large \( \beta \) to find minimum \( V' = f^3 [4F(\lambda(f)) + \beta F'(\lambda(f))] = 0 \)

Theory not conformal at scale f - no light dilaton

\[ m^2_{\text{dil}} \sim 256\pi^2 f^2 \sim \Lambda^2 \quad 3 \text{ TeV not 125 GeV} \]

OR we can tune away the quartic to get a nearly flat-direction
Light Dilaton?

- Generically, dilaton is not light unless the quartic is suppressed relative to NDA.
- To get a light dilaton, need flat direction in vicinity of near-zero in $\beta$-function.
- While this is natural in SUSY theories, it is not the case in non-supersymmetric ones.

Non-SUSY light dilaton:

$$F(\lambda) = a + \delta F(\lambda)$$

$$F \sim a = O(\delta F) \text{ by tuning}$$

$0 \quad \delta F \quad a \quad 16\pi^2$
The 3-2 Model

light dynamical perturbative dilaton

\[
\begin{array}{c|cc|cc}
 & SU(3) & SU(2) & U(1) & U(1)_R \\
\hline
Q & \Box & \Box & 1/3 & 1 \\
L & 1 & \Box & -1 & -3 \\
\bar{U} & \Box & 1 & -4/3 & -8 \\
\bar{D} & \Box & 1 & 2/3 & 4 \\
\end{array}
\]

classical flat directions:

\[Q\bar{D}L, \ Q\bar{U}L \ \det(\bar{Q}Q)\]

lifted by non-perturbative ADS superpotential and tree level perturbative superpotential:

\[
W_{\text{dyn}} = \frac{\Lambda_3^7}{\det(\bar{Q}Q)} \quad W = \lambda Q\bar{D}L
\]

light dilaton: \(m_{\text{dil}} \approx \lambda f \approx \lambda^6 \Lambda_3\)

But SUSY played crucial role here
The EWSB line-up

- SM: valid up to Planck, ~0.000...%
- MSSM: ~0.1%
- Composite Higgs: ~few%
- Dilaton: ~few%

Color code: natural (left) to unnatural (right)

Dilaton and composite Higgs in a similar strained state
Dilaton Couplings

- Presume have a strongly coupled conformal sector coupled to weak fundamental sector
- Strong sector has SBSI
- derive interactions of mass eigenstates with dilaton
The low-energy effective theory, valid below the scale \( \Lambda \), is determined by the Lagrangian

\[
L_{\text{CFT}}^{\text{UV}} = \sum_i g_i O_i^{\text{UV}}
\]

For terms involving no explicit symmetry breaking we have

\[
[g_i] = 4 - \Delta_i^{\text{UV}}
\]

where \( \Delta_i^{\text{UV}} \) is an unknown function of the scale invariant couplings and we have expanded in \( \mu \rightarrow 0 \).

In IR, different dof compensate

\[
L_{\text{CFT}}^{\text{IR}} = \sum_j c_j (\prod g_i^{n_i}) O_j^{\text{IR}} \chi^{m_j}
\]

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

Single power of exp. breaking:

\[
L_{\text{breaking}}^{\text{IR}} = \sum_j c_j g_i (\Delta_i^{\text{UV}} - \Delta_j^{\text{IR}}) O_j^{\text{IR}} \frac{\sigma}{f}
\]

No exp. breaking:

\[
L_{\text{symmetric}}^{\text{IR}} = \sum_j c_j (4 - \Delta_j^{\text{IR}}) O_j^{\text{IR}} \frac{\sigma}{f}
\]

rescaled tree-level SM

\[
\frac{\sigma}{f} T_\mu^\nu = \frac{v}{f} \sigma \left\{ [2m_W^2 W_\mu^2 + m_Z^2 Z^2 + m_\psi \psi \ldots] + 2 \frac{\beta_s}{g} G_{\mu\nu}^2 + 2 \frac{\beta_F}{e} F_{\mu\nu}^2 \right\}
\]

SM beta-functions
Dilaton couplings
Partial Compositeness

\[ L^\text{UV}_{\text{CFT}} + L_{\text{elem}} + \sum_i y_i O_{\text{elem},i} O^\text{UV}_{\text{CFT},i} \]

spurion dimensions

\[ [y_i] = 4 - \Delta^\text{UV}_{\text{CFT},i} - \Delta^\text{UV}_{\text{elem},i} \]

VEV: \( \langle O(x) \rangle = f^\Delta \)

compensate

\[ L^\text{IR}_{\text{CFT}} + L_{\text{elem}} + \sum_i y_i O_{\text{elem},i} O^\text{IR}_{\text{CFT},i} \times \chi(\Delta^\text{UV}_{\text{CFT},i} - \Delta^\text{IR}_{\text{CFT},i} + \Delta^\text{UV}_{\text{elem},i} - \Delta^\text{IR}_{\text{elem},i}) \]
Dilaton-Fermion Couplings

\[ \mathcal{L}_{\text{mix}} = y_L \psi_L \Theta_R + y_R \psi_R \Theta_L \]

\[ [y_{R,L}] = -\gamma_{L,R} \]

Exponential running of \( y \)'s generates large mass hierarchies

Integrate out heavy composites and compensate:

\[ \mathcal{L}_{\text{eff}} = -M y_L y_R \psi_L \psi_R \chi^m \]

\[ m = \Delta_{\psi_L}^{UV} - \Delta_{\psi_L}^{IR} + \Delta_{\psi_R}^{UV} - \Delta_{\psi_R}^{IR} + \Delta_{\theta_L}^{UV} + \Delta_{\theta_R}^{UV} - 4 \]

\[ \mathcal{L} \supset m_{\psi} \psi_L \psi_R \left[ 1 + \frac{\sigma}{f} (1 + \gamma_L + \gamma_R) \right] \]

Enhancement in couplings to partially composite fermions
Couplings to massless gauge fields

\[ \mathcal{L}_{mix} \supset -\frac{1}{4g^2} F_{\mu\nu}^2 + A_\mu J^\mu \]

coupling to CFT and fundamental currents

integrate out the CFT:

\[ -\frac{1}{4g^2(\mu)} F_{\mu\nu}^2 \]

compensate: \( f \longrightarrow f\chi = f e^{\sigma/f} \)

\[ \mathcal{L} = -\frac{1}{2} \left( \frac{\beta_{IR}}{g} - \frac{\beta_{UV}}{g} \right) \frac{\sigma}{v} F_{\mu\nu}^2 \]

Depends on UV contributions to \( \beta \)-function

UV completion - embedding of SM gauge group
Couplings - Summary

Overall rescaling

\[ \mathcal{L} = \frac{v}{f} \sigma \left\{ 2m_W^2 W_\mu^2 + m_Z^2 Z^2 + m_\psi \psi (1 + \gamma) \psi \ldots \right\} + 2(\beta_{UV} - \beta_{IR})/g F^{2}_{\mu\nu} \]

Anomalous dim.

Beta-functions

\[ SM \times \frac{v}{f} \]

\[ SM \times \frac{v}{f} (1 + \gamma) \]

\[ \frac{v}{f} (\beta_{UV} - \beta_{IR} + \text{loops}) \]
With this we can compute the rates as approximated (if the deviations of the couplings are small) by anomalous dimensions.

Our theoretical predictions with the experimental values of the rates \[38\]. It is useful to individual coefficients by fitting the.

There is already an extensive literature on constraints for the coefficients. We have assumed.

Figure 1: Left: Constraints on the \(j\) symmetry, one typically expects tree-level contributions coming from (2.31) to contributions to the vector boson self energies. When compared to the SM prediction, the additional yields the 99% CL allowed region \(0\) \(2\) dilaton scenario one expects.

Previous to the recent discovery at the LHC, indirect contraints on the higgs couplings, in the process could be larger than in SM.

 unless the coupling to gluons is enhanced by a large.

Generic predictions for the dilaton are then an overall suppression of all decay rates.

The dilaton production cross sections will also di...
Enhanced diphoton may be telling us about matter content

New 2012 data will put stronger constraints on UV parameters
Conclusions

• The 125 GeV resonance may be a dilaton - well motivated

• Large NDA quartic in non-SUSY theories
  • hard to stabilize without raising mass - Fine tuning
  • need flat direction in vicinity of near-marginality

• Once it is light, couplings fixed up to a few parameters associated with conformal dynamics and embedding
  • $v/f$ suppressed, $\beta$’s and $\gamma$’s fix the rest

• “Higgs” is a chance to probe strong sector!