Distinguishing a light dilaton from a light Higgs

Heather Logan
Carleton University

The Next Stretch of the Higgs Magnificent Mile
Northwestern University (Chicago campus), May 14–16, 2012

Outline

Introduction

Dilaton couplings, production, and decay

Constraints from LEP and LHC

A 125 GeV dilaton?

Future prospects

Conclusions
Introduction: what is a dilaton

Dilaton is the Goldstone boson associated with spontaneously broken scale invariance.

Gildener & Weinberg, PRD 13, 3333 (1976)
Goldberger, Grinstein & Skiba, PRL 100, 111802 (2008)
Fan, Goldberger, Ross & Skiba, PRD 79, 035017 (2009)
Vecchi, PRD 82, 076009 (2010)

Can be much lighter than conformal-breaking scale $f$ in strongly-coupled conformal EWSB theories

Expect $f > v$: dilaton is not responsible for EWSB

Introduce in the low-energy Lagrangian as a compensator for scale transformations:
insert powers of $\bar{\chi}/f \equiv (1 + \chi/f)$ to make $\mathcal{L}$ terms dimension-4
Dilaton couplings: tree level

Insert powers of $\bar{\chi}/f \equiv (1 + \chi/f)$ to make $\mathcal{L}$ terms conformal:

$$\mathcal{L} = \frac{v^2}{4} \text{Tr} |D_\mu U|^2 (\bar{\chi}/f)^2 - m_i \bar{\psi}_i U \psi_i (\bar{\chi}/f) + \cdots$$

$U$ is the nonlinear sigma field for the EWSB Goldstones $\pi^a$:

$$U = \exp \left[ i (\pi^a \tau^a / v) (f / \bar{\chi}) \right]$$

Couplings of the physical dilaton $\chi$ up to dimension 4:

$$\mathcal{L} = \frac{1}{2} \frac{M_V^2}{v} V_\mu V^\mu \left( \frac{2\chi}{f} + \frac{\chi^2}{f^2} \right) - \frac{\chi}{f} m_i \bar{\psi}_i \psi_i + \cdots$$

Compare the SM Higgs:

$$\mathcal{L} = \frac{1}{2} \frac{M_V^2}{v} V_\mu V^\mu \left( \frac{2h}{v} + \frac{h^2}{v^2} \right) - \frac{h}{v} m_i \bar{\psi}_i \psi_i + \cdots$$

$\chi_{VV}$ and $\chi_{f\bar{f}}$ couplings are equal to corresponding SM Higgs couplings but with an extra factor of $v/f$. 
Dilaton couplings: loop induced

Gauge field strength terms are already conformal, except for running at 1-loop: conformal-restoring terms $\propto$ beta function

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_{\text{EM}}}{8\pi}b_{\text{EM}}F_{\mu\nu}F^{\mu\nu}\ln(\bar{\chi}/f)$$

$$-\frac{1}{4}G_{\mu\nu}^aG^{a\mu\nu} - \frac{\alpha_s}{8\pi}b_G G_{\mu\nu}^aG^{a\mu\nu}\ln(\bar{\chi}/f) + \cdots$$

Full SM beta function coefficients (including top quark):

$$b_G = 11 - (2/3)n_f = 7, \quad b_{\text{EM}} = -11/3$$

Pointlike dimension-5 operators coupling $\chi$ to $gg, \gamma\gamma$ after expanding the log.

Rather mysterious...
Dilaton couplings: loop induced

Another way to understand the couplings to massless vectors:

If EM, QCD are part of the conformal sector, their beta functions must be zero above the conformal-breaking scale.

\[ \sum_{\text{light}} b_i + \sum_{\text{heavy}} b_i = 0 \]

New stuff must run in the loops to cancel the SM beta function. ⇒ This new stuff also runs in the \( \chi gg, \chi \gamma \gamma \) loops!

\[
\mathcal{L} = \frac{\alpha_{EM}}{8\pi} \left( \sum_{\text{heavy}} b^i_{EM} + \text{SM loops} \right) F_{\mu\nu} F^{\mu\nu} \frac{\chi}{f} \\
= \frac{\alpha_{EM}}{8\pi} (-b_{EM} + \text{SM loops}) F_{\mu\nu} F^{\mu\nu} \frac{\chi}{f}
\]

and similar for QCD. \( b_{EM} \equiv \sum_{\text{light}} b^i_{EM} = -11/3 \)

Key assumption: EM, QCD are also conformal in high-energy theory!
Dilaton couplings: loop induced

Define scaling factors in terms of SM Higgs 1-loop coupling:

\[ R_g = \left| \frac{-b_G + \frac{1}{2} \sum_i F_{1/2}(\tau_i)}{\frac{1}{2} \sum_i F_{1/2}(\tau_i)} \right|^2, \quad R_\gamma = \left| \frac{-b_{EM} + \sum_i N_{ci} Q_i^2 F_i(\tau_i)}{\sum_i N_{ci} Q_i^2 F_i(\tau_i)} \right|^2 \]

\( gg \to \chi \) cross section, \( \chi \to gg, \gamma\gamma \) partial widths scaled compared to SM Higgs as

\[ \frac{v^2}{f^2} R_g, \quad \frac{v^2}{f^2} R_\gamma \]
QCD running quite strong
→ large beta function, $R_g \approx 140$ for $M_\chi = 125$ GeV

EM running weaker
→ beta function fairly small, $R_\gamma \approx 2.43$ for $M_\chi = 125$ GeV
Dilaton production: simple scaling from SM Higgs rates

LEP, ILC:

\[
\frac{\sigma(e^+e^- \rightarrow Z\chi)}{\sigma(e^+e^- \rightarrow ZH_{SM})} = \frac{v^2}{f^2}
\]

LHC:

\[
\begin{align*}
\frac{\sigma(gg \rightarrow \chi)}{\sigma(gg \rightarrow H_{SM})} &= \frac{v^2}{f^2} R_g \\
\frac{\sigma(VBF \rightarrow \chi)}{\sigma(VBF \rightarrow H_{SM})} &= \frac{v^2}{f^2} \\
\frac{\sigma(q\bar{q} \rightarrow V\chi)}{\sigma(q\bar{q} \rightarrow VH_{SM})} &= \frac{v^2}{f^2}
\end{align*}
\]

Photon collider:

\[
\frac{\sigma(\gamma\gamma \rightarrow \chi)}{\sigma(\gamma\gamma \rightarrow H_{SM})} = \frac{v^2}{f^2} R_\gamma
\]

Heather Logan (Carleton U.) Light dilaton vs. Higgs Higgs Magnificent Mile 2012
Dilaton decays

Main differences from SM Higgs:
- All tree-level partial widths scaled by $v^2/f^2$
- Partial widths to $gg, \gamma\gamma$ scaled by $R_g v^2/f^2, R_\gamma v^2/f^2$

Coleppa, Gregoire & HEL, PRD85, 055001 (2012)

Heather Logan (Carleton U.) Light dilaton vs. Higgs Higgs Magnificent Mile 2012
Dilaton decays

\( gg \) is dominant decay below 160 GeV: all other BRs suppressed

Coleppa, Gregoire & HEL, PRD85, 055001 (2012)
**LEP constraints:** extrapolated from Higgs search

Coleppa, Gregoire & HEL, PRD85, 055001 (2012)

Excludes $f \lesssim 400$ GeV

**Solid:** $e^+e^- \rightarrow Z\chi$, $\chi \rightarrow bb$ and $\tau\tau$ [LEP final combination, PLB565, 61 (2003)]

**Dash-dot:** $\chi \rightarrow$ hadrons ($bb + cc + gg$) [LEP Higgs WG, hep-ex/0107034]

Heather Logan (Carleton U.) Light dilaton vs. Higgs Higgs Magnificent Mile 2012
LHC constraints

From ATLAS + CMS SM Higgs searches, 1.0–2.3 fb$^{-1}$ at 7 TeV (Lepton-Photon 2011)

![Graph showing LHC constraints on a 2D plot with Higgs mass vs. coupling strength.]

Coleppa, Gregoire & HEL, PRD85, 055001 (2012)

\[
\frac{\sigma(pp \to \chi)}{\sigma(pp \to H_{SM})} = \frac{v^2 R_g \sigma(gg \to H_{SM}) + \sigma(VBF \to H_{SM})}{f^2 \sigma(gg \to H_{SM}) + \sigma(VBF \to H_{SM})}
\]

Heather Logan (Carleton U.) Light dilaton vs. Higgs

Higgs Magnificent Mile 2012
LHC constraints
Updated with full-2011-dataset $\gamma\gamma$ analyses (Moriond 2012)

$\sigma/\sigma_{SM} = 0.1$

Dots: inclusive $\chi \rightarrow \gamma\gamma$

Dashes: inclusive $\chi \rightarrow WW$

Exclusion from $\gamma\gamma$ channel

Excluded by LHC

ATLAS
CMS

Heather Logan (Carleton U.) Light dilaton vs. Higgs Higgs Magnificent Mile 2012
A 125 GeV dilaton?

LHC diphoton excess is consistent with a light dilaton

CMS, $\sqrt{s} = 7$ TeV
$L = 4.6-4.8$ fb$^{-1}$

$\sigma_{\text{Higgs}} / \sigma_{\text{SM}}$

CMS, $\sqrt{s} = 7$ TeV
$L = 4.6-4.8$ fb$^{-1}$

$H \rightarrow \gamma\gamma$
$H \rightarrow WW$
$H \rightarrow bb$
$H \rightarrow ZZ \rightarrow 4l$

Heather Logan (Carleton U.)
Light dilaton vs. Higgs
Higgs Magnificent Mile 2012

CMS, arXiv:1202.1488
A 125 GeV dilaton?

\[ \frac{BR(\chi \rightarrow \gamma\gamma)}{BR(\chi \rightarrow ZZ)} \simeq 2.43 \times SM \]

- Inclusive \( pp \rightarrow \chi \rightarrow WW, \tau\tau, \) etc.: same suppression as \( ZZ \)

\[ BR(\chi \rightarrow \gamma\gamma) = 0.200 \times SM, \quad BR(\chi \rightarrow ZZ) = 0.0823 \times SM \]

\[ \frac{\sigma(gg \rightarrow \chi)}{\sigma(VBF \rightarrow \chi)} \simeq 140 \times SM \]

- Associated \( W\chi, Z\chi \) production: same suppression as VBF

<table>
<thead>
<tr>
<th></th>
<th>Inclusive ( pp \rightarrow \chi \rightarrow \gamma\gamma )</th>
<th>2 \times SM</th>
<th>1 \times SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f )</td>
<td></td>
<td>886 GeV</td>
<td>1253 GeV</td>
</tr>
<tr>
<td>( \sigma(gg \rightarrow \chi) )</td>
<td></td>
<td>10.8 \times SM</td>
<td>5.39 \times SM</td>
</tr>
<tr>
<td>( \sigma(VBF \rightarrow \chi) )</td>
<td></td>
<td>7.71% \times SM</td>
<td>3.85% \times SM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Inclusive ( pp \rightarrow \chi \rightarrow ZZ )</th>
<th>0.823 \times SM</th>
<th>0.411 \times SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF ( \rightarrow \chi \rightarrow \gamma\gamma )</td>
<td></td>
<td>1.54% \times SM</td>
<td>0.77% \times SM</td>
</tr>
<tr>
<td>VBF ( \rightarrow \chi \rightarrow \tau\tau )</td>
<td></td>
<td>0.63% \times SM</td>
<td>0.32% \times SM</td>
</tr>
</tbody>
</table>

Heather Logan (Carleton U.)  Light dilaton vs. Higgs  Higgs Magnificent Mile 2012
Distinguishing features

- Severe suppression of VBF, $WH/ZH$ associated production
  Signals $\mathcal{O}(1\%)$ SM rate
  \[
  \frac{\sigma(gg \to \chi) / \sigma(VBF \to \chi)}{\sigma(VBF \to \chi)} = 140 \times \text{SM} \iff \text{measure } R_g?? \ (\text{lower bound})
  \]

- Relative rates in $\gamma\gamma$ compared to $WW$, $ZZ$
  \[
  \frac{\text{BR}(\chi \to \gamma\gamma) / \text{BR}(\chi \to ZZ)}{\text{BR}(\chi \to ZZ)} = 2.43 \times \text{SM} \iff \text{measure } R_\gamma!
  \]

- $Z\gamma$ final state provides one more distinctive handle
  $R_{Z\gamma}$ related to $\beta$-function for $\sin^2 \theta_W$

- Can’t make direct measurement of $v^2/f^2$ without model assumptions about BRs. Dominant decay into $gg$ not detectable at LHC.

- Dilaton contributes only $v^2/f^2$ of the “Higgs exchange” amplitude needed to unitarize longitudinal $WW$ scattering:
  $\rightarrow$ expect additional strong-dynamics effects near TeV scale.

*Heather Logan (Carleton U.) Light dilaton vs. Higgs Higgs Magnificent Mile 2012*
Distinguishing features: a caveat

Predictions of $R_g = 140$, $R_\gamma = 2.43$ (for $M_\chi = 125$ GeV) rely on QCD, EM being part of the conformal sector.

An exception: Radion in Randall-Sundrum models. Dual to dilaton, except for bulk contributions to $R_{gg}$, $R_{\gamma\gamma}$.

gg, $\gamma\gamma$ couplings $\sim \left[ \frac{1}{kL} + \frac{\alpha_s, EM}{2\pi} b_{G, EM} \right]$, $kL = 35$

![Graph showing cross section ratios](image)

Barger, Ishida & Keung, arXiv:1111.4473

Heather Logan (Carleton U.) Light dilaton vs. Higgs Higgs Magnificent Mile 2012

18
ILC prospects: $v^2/f^2$ cross section suppression hurts a lot but ILC buys you model-independent measurement of $f$ from $\sigma(e^+e^- \rightarrow Z\chi)$ and access to dominant $gg$ decay mode.

Coleppa, Gregoire & HEL, PRD85, 055001 (2012)

<table>
<thead>
<tr>
<th>Inclusive $pp \rightarrow \chi \rightarrow \gamma\gamma$</th>
<th>$2 \times$ SM</th>
<th>$1 \times$ SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>886 GeV</td>
<td>1253 GeV</td>
</tr>
<tr>
<td>$\sigma(e^+e^- \rightarrow Z\chi)$</td>
<td>$7.71% \times$ SM</td>
<td>$3.85% \times$ SM</td>
</tr>
</tbody>
</table>

Heather Logan (Carleton U.) Light dilaton vs. Higgs Higgs Magnificent Mile 2012
Photon collider prospects:

$\gamma\gamma \rightarrow \chi$ coupling enhancement makes rate only a little better

No decay-mode–independent production rate measurement at PC

Coleppa, Gregoire & HEL, PRD85, 055001 (2012)

<table>
<thead>
<tr>
<th>Inclusive $pp \rightarrow \chi \rightarrow \gamma\gamma$</th>
<th>$2 \times SM$</th>
<th>$1 \times SM$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>886 GeV</td>
<td>1253 GeV</td>
</tr>
<tr>
<td>$\sigma(\gamma\gamma \rightarrow \chi)$</td>
<td>18.7% $\times SM$</td>
<td>9.37% $\times SM$</td>
</tr>
</tbody>
</table>

Heather Logan (Carleton U.)  Light dilaton vs. Higgs  Higgs Magnificent Mile 2012
More exotic dilaton features: $\chi\chi VV$ couplings

Couplings of the physical dilaton $\chi$ up to dimension 4:

$$\mathcal{L} = \frac{1}{2} M_V^2 V_\mu V^\mu \left( \frac{2\chi}{f} + \frac{\chi^2}{f^2} \right) - \frac{\chi}{f} m_i \bar{\psi}_i \psi_i + \cdots$$

Compare the SM Higgs:

$$\mathcal{L} = \frac{1}{2} M_V^2 V_\mu V^\mu \left( \frac{2h}{v} + \frac{h^2}{v^2} \right) - \frac{h}{v} m_i \bar{\psi}_i \psi_i + \cdots$$

SM Higgs $hhW_\mu W^\nu$ coupling is pure gauge, $\propto g^2$
- True for any SU(2) doublet scalar, no matter its vev

Dilaton $\chi\chi W_\mu W^\nu$ coupling is $\propto g^2 v^2 / f^2$
- Consistent with SM Higgs mixed with SU(2) singlet, with new stuff in $gg, \gamma\gamma$ loops.
- Distinguish dilaton from SM Higgs mixed with inert doublet.
- Not easy to measure: need double dilaton production.
More exotic dilaton features: dilaton self-coupling

In pure conformal theory, dilaton is derivatively self-coupled

Explicit breaking of CFT generates non-derivative couplings—and a nonzero mass—for $\chi$

Generally get a triple-dilaton coupling different from the corresponding triple-SM-Higgs coupling; details depend on nature of the explicit conformal-breaking operator.

Goldberger, Grinstein & Skiba, arXiv:0708.1463

Again not easy to measure: need double dilaton production.
- LHC: rates very low, backgrounds very challenging, need to disentangle from $\chi\chi gg$ coupling.
- ILC: rates even more suppressed than SM Higgs, need to disentangle from $\chi\chi VV$ coupling.
Conclusions

The ATLAS/CMS excess in diphotons at \( \sim 125 \text{ GeV} \) is consistent with a light dilaton with \( f \sim 800–1300 \text{ GeV} \).

Distinguishing a 125 GeV dilaton from the SM Higgs is actually pretty straightforward:
- \( \text{BR}(\chi \rightarrow \gamma\gamma)/\text{BR}(\chi \rightarrow ZZ) \sim 2.43 \times \text{SM} \)
- VBF, \( W\chi/Z\chi \) associated production \( \sim 1\% \times \text{SM} \)

Predictions are based on QED, QCD being part of conformal sector

Dilaton does not fully unitarize longitudinal \( WW \) scattering: expect strong-dynamics effects around TeV scale

Heather Logan (Carleton U.) Light dilaton vs. Higgs Higgs Magnificent Mile 2012