Distinguishing a light dilaton from a light Higgs

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

Based mostly on B. Coleppa, T. Grégoire and H.E.L., arXiv:1111.3276

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:

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

U is the nonlinear sigma field for the EWSB Goldstones π^a:

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

Couplings of the physical dilaton χ 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:

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

χVV 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

$$\begin{aligned}\mathcal{L} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha_{\mathrm{EM}}}{8\pi}b_{\mathrm{EM}}F_{\mu\nu}F^{\mu\nu}\ln(\bar{\chi}/f) \\ &\quad -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - \frac{\alpha_s}{8\pi}b_G G^a_{\mu\nu}G^{a\mu\nu}\ln(\bar{\chi}/f) + \cdots\end{aligned}$$

Full SM beta function coefficients (including top quark):

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

Pointlike dimension-5 operators coupling χ 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.
$\Rightarrow$ This new stuff also runs in the χgg, $\chi\gamma\gamma$ loops!

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

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

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:

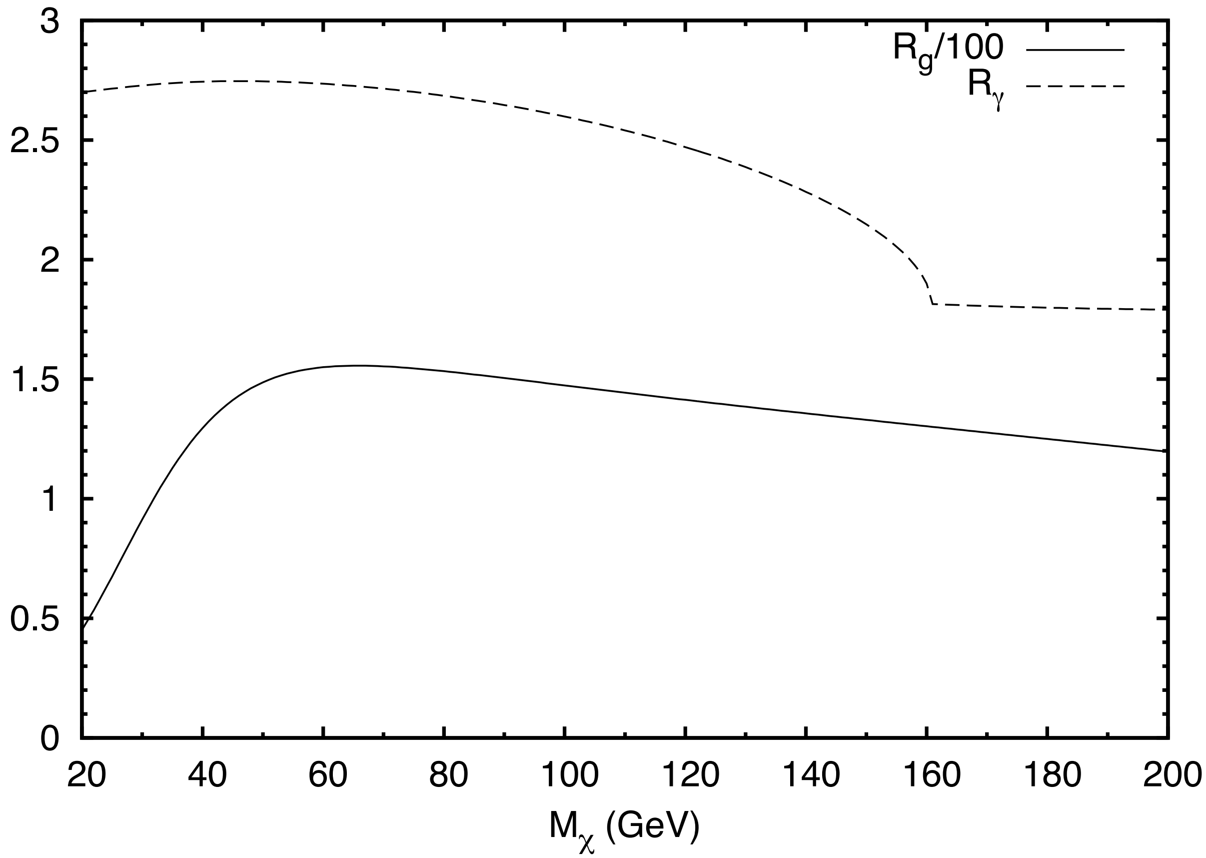
$$R_g = \frac{\left| -b_G + \frac{1}{2}\sum_i F_{1/2}(\tau_i) \right|^2}{\left| \frac{1}{2}\sum_i F_{1/2}(\tau_i) \right|^2}, \qquad R_\gamma = \frac{\left| -b_{\mathrm{EM}} + \sum_i N_{ci} Q_i^2 F_i(\tau_i) \right|^2}{\left| \sum_i N_{ci} Q_i^2 F_i(\tau_i) \right|^2}$$

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

$$\frac{v^2}{f^2} R_g, \qquad \frac{v^2}{f^2} R_\gamma$$

QCD running quite strong
$\rightarrow$ large beta function, $R_g \simeq 140$ for $M_\chi = 125$ GeV

EM running weaker
$\rightarrow$ beta function fairly small, $R_\gamma \simeq 2.43$ for $M_\chi = 125$ GeV



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

Dilaton production: simple scaling from SM Higgs rates

LEP, ILC:

$$\frac{\sigma(e^+e^- \to Z\chi)}{\sigma(e^+e^- \to ZH_{\text{SM}})} = \frac{v^2}{f^2}$$

LHC:

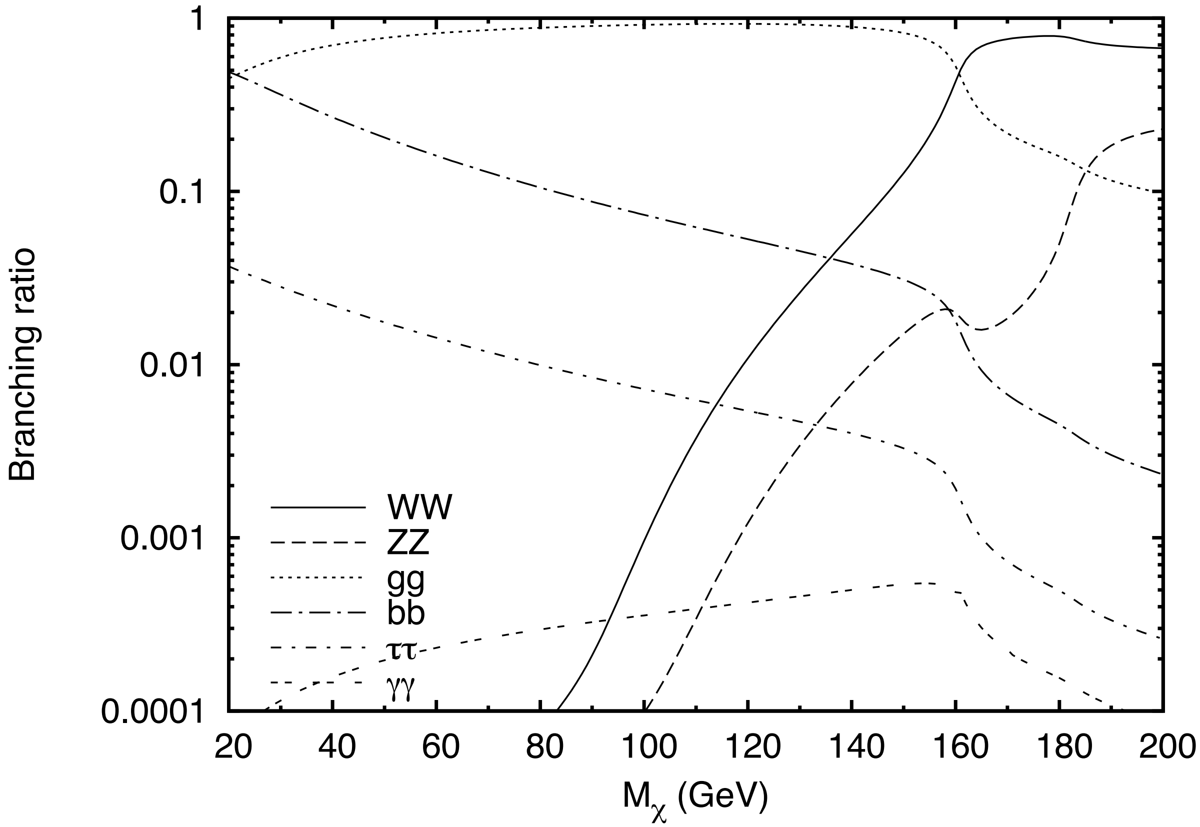
$$\begin{aligned}\frac{\sigma(gg \to \chi)}{\sigma(gg \to H_{\text{SM}})} &= \frac{v^2}{f^2} R_g \\ \frac{\sigma(\text{VBF} \to \chi)}{\sigma(\text{VBF} \to H_{\text{SM}})} &= \frac{v^2}{f^2} \\ \frac{\sigma(q\bar{q} \to V\chi)}{\sigma(q\bar{q} \to VH_{\text{SM}})} &= \frac{v^2}{f^2}\end{aligned}$$

Photon collider:

$$\frac{\sigma(\gamma\gamma \to \chi)}{\sigma(\gamma\gamma \to H_{\text{SM}})} = \frac{v^2}{f^2} R_\gamma$$

Dilaton decays

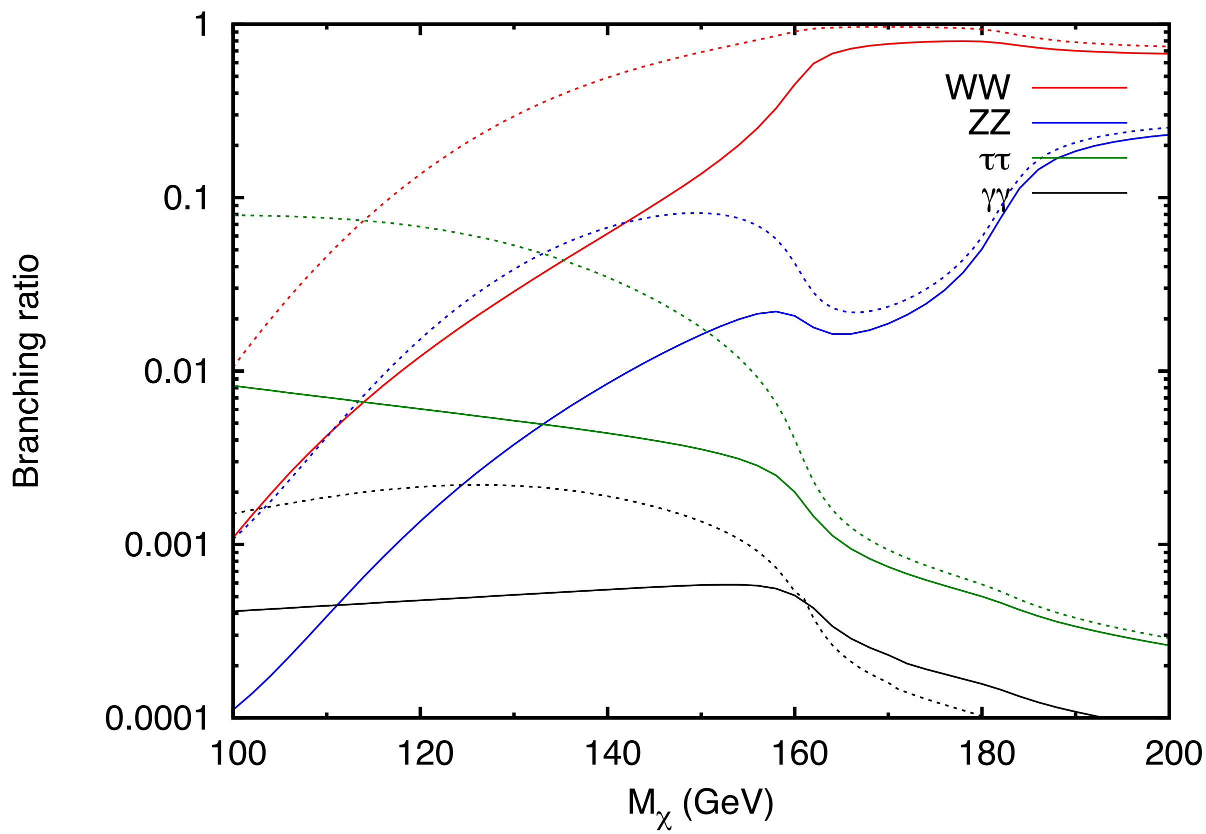
Main differences from SM Higgs:
- All tree-level partial widths scaled by v^2/f^2
- Partial widths to gg, $\gamma\gamma$ scaled by $R_g v^2/f^2$, $R_\gamma v^2/f^2$



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

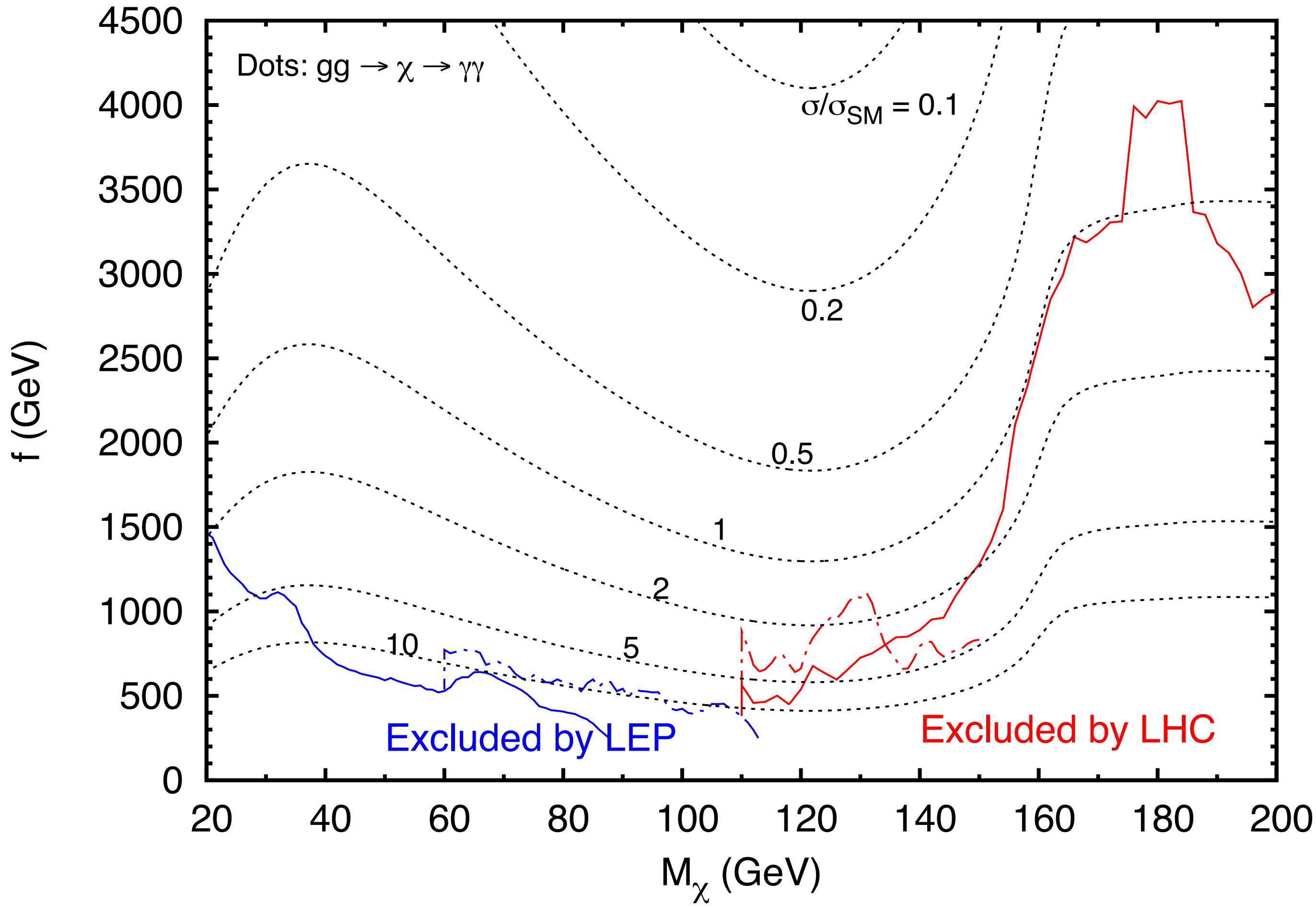
Dilaton decays

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)

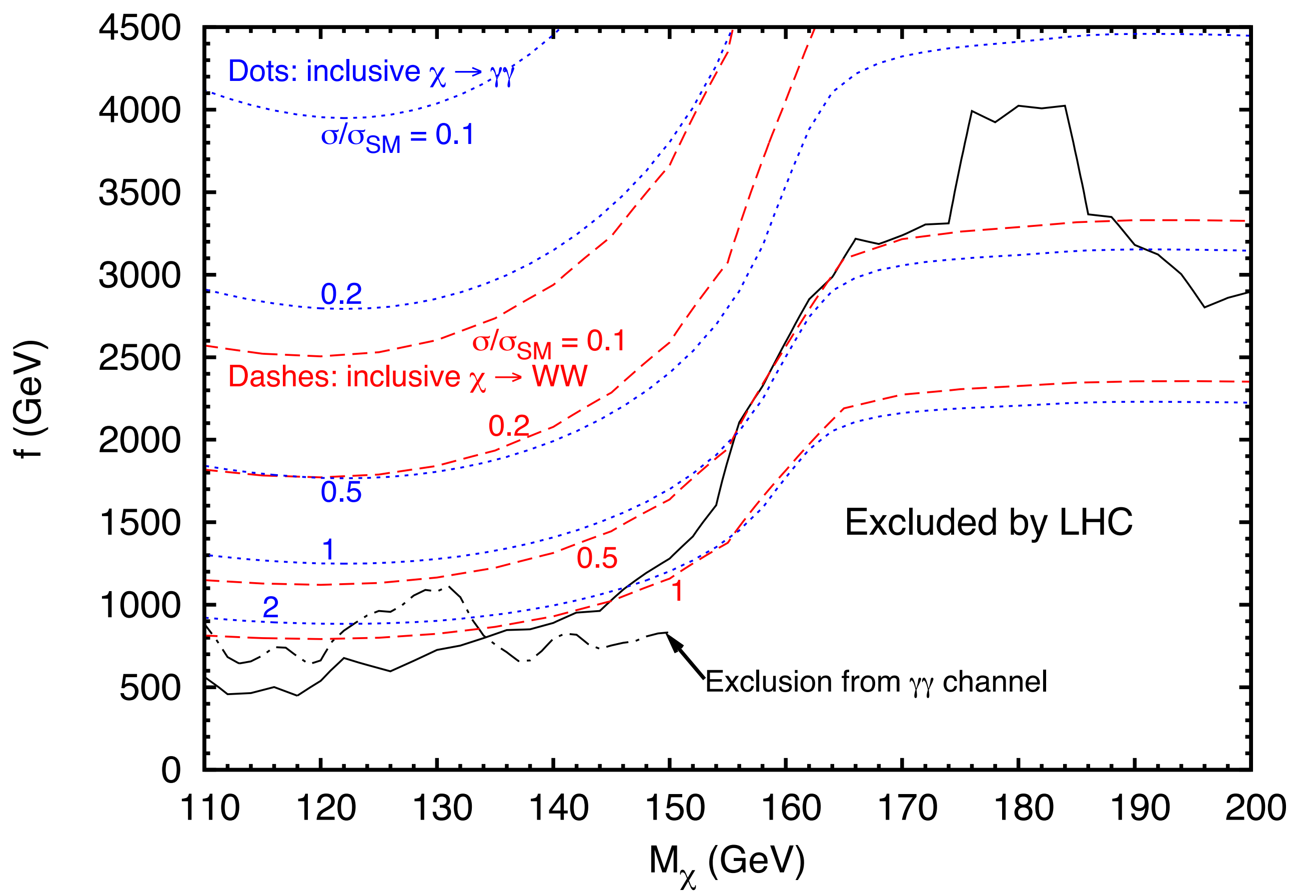
Excludes $f \lesssim 400$ GeV

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

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

LHC constraints

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

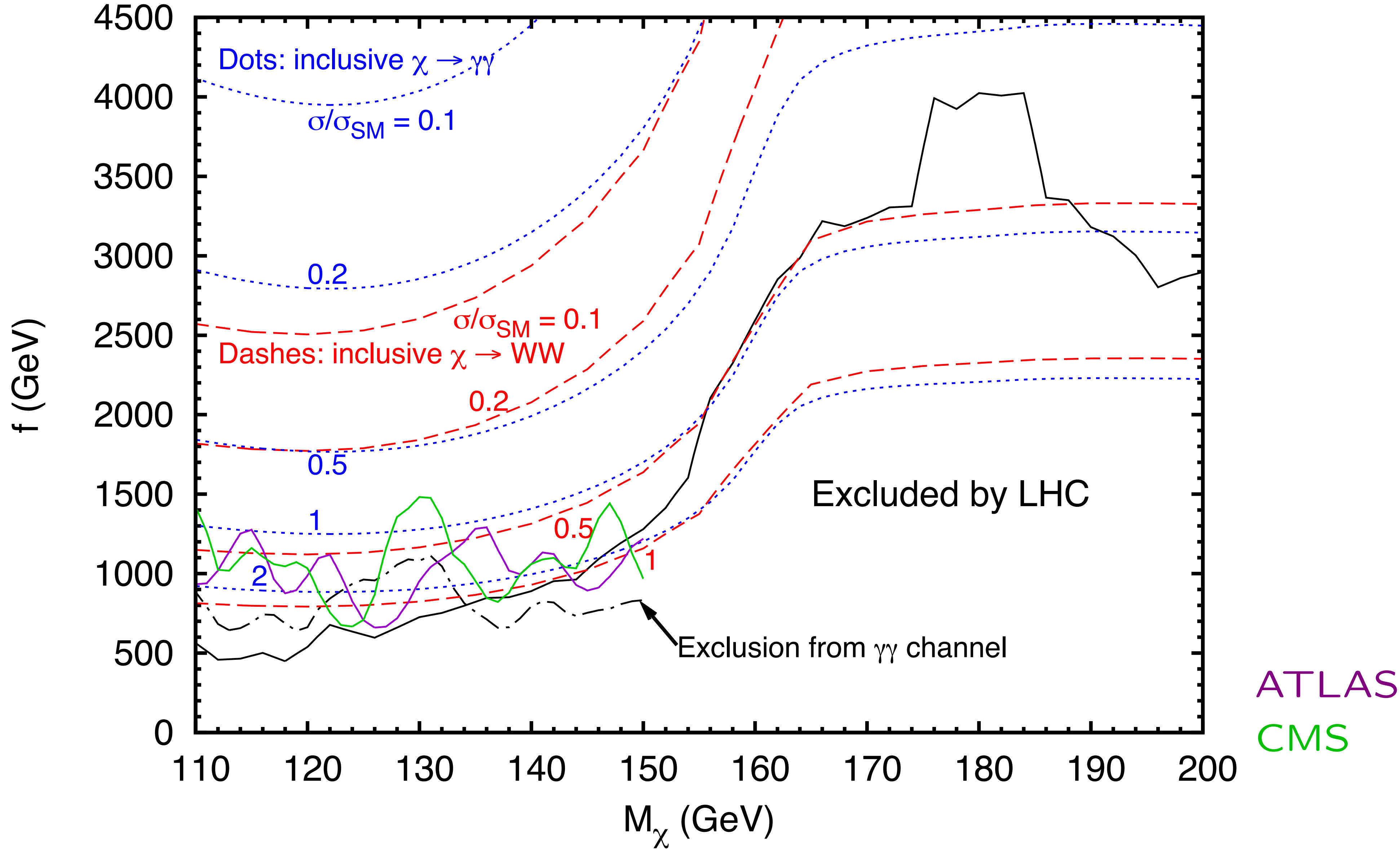


Coleppa, Gregoire & HEL, PRD85, 055001 (2012)

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

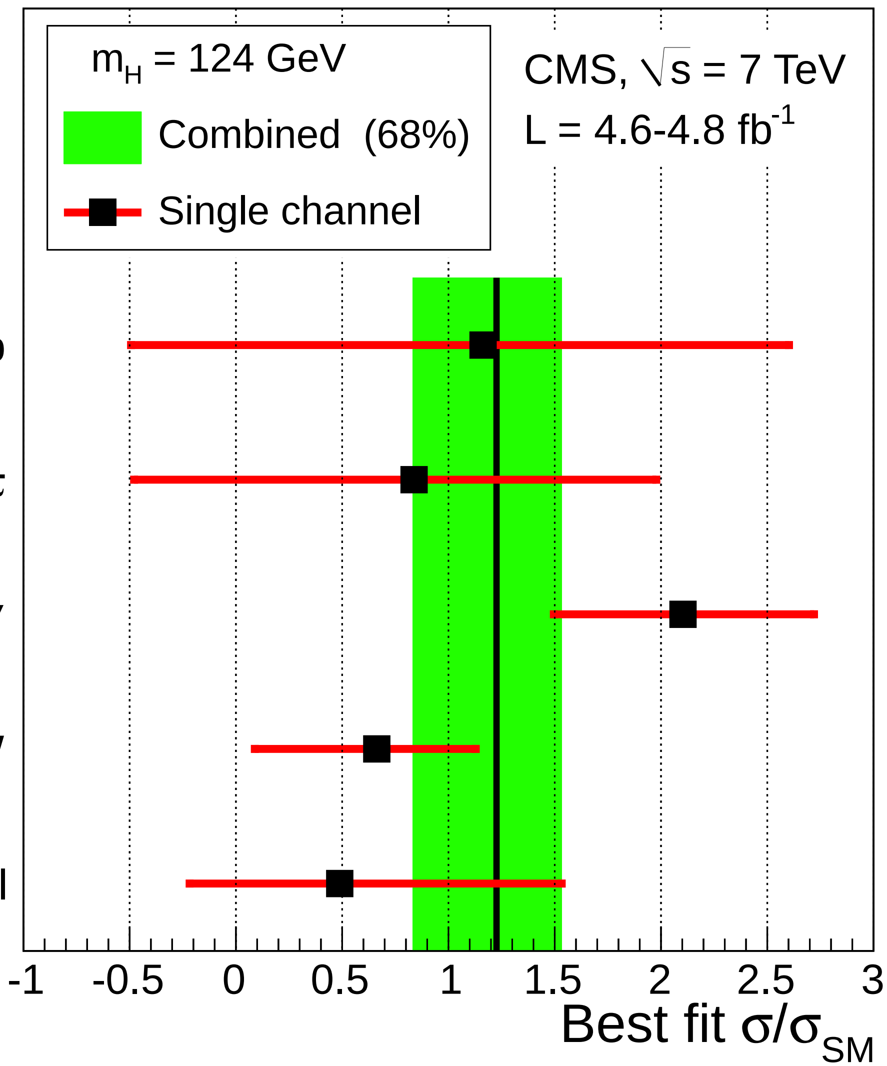
LHC constraints

Updated with full-2011-dataset $\gamma\gamma$ analyses (Moriond 2012)



A 125 GeV dilaton?

LHC diphoton excess is consistent with a light dilaton



CMS, arXiv:1202.1488

A 125 GeV dilaton?

$\text{BR}(\chi \to \gamma\gamma)/\text{BR}(\chi \to ZZ) \simeq 2.43 \times \text{SM}$

- Inclusive $pp \to \chi \to WW$, $\tau\tau$, etc.: same suppression as ZZ

$\text{BR}(\chi \to \gamma\gamma) = 0.200 \times \text{SM}$, $\text{BR}(\chi \to ZZ) = 0.0823 \times \text{SM}$

$\sigma(gg \to \chi)/\sigma(\text{VBF} \to \chi) \simeq 140 \times \text{SM}$

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

Inclusive $pp \to \chi \to \gamma\gamma$	$2 \times$ SM	$1 \times$ SM
f	886 GeV	1253 GeV
$\sigma(gg \to \chi)$	$10.8 \times$ SM	$5.39 \times$ SM
$\sigma(\text{VBF} \to \chi)$	$7.71\% \times$ SM	$3.85\% \times$ SM
Inclusive $pp \to \chi \to ZZ$	$0.823 \times$ SM	$0.411 \times$ SM
$\text{VBF} \to \chi \to \gamma\gamma$	$1.54\% \times$ SM	$0.77\% \times$ SM
$\text{VBF} \to \chi \to \tau\tau$	$0.63\% \times$ SM	$0.32\% \times$ SM

Distinguishing features

- Severe suppression of VBF, WH/ZH associated production

  Signals $\mathcal{O}(1\%)$ SM rate

  $\sigma(gg \to \chi)/\sigma(\text{VBF} \to \chi) = 140 \times$ SM $\Leftarrow$ measure R_g?? (lower bound)

- Relative rates in $\gamma\gamma$ compared to WW, ZZ

  $\text{BR}(\chi \to \gamma\gamma)/\text{BR}(\chi \to ZZ) = 2.43 \times$ SM $\Leftarrow$ measure R_γ!

- $Z\gamma$ final state provides one more distinctive handle

  $R_{Z\gamma}$ related to β-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.

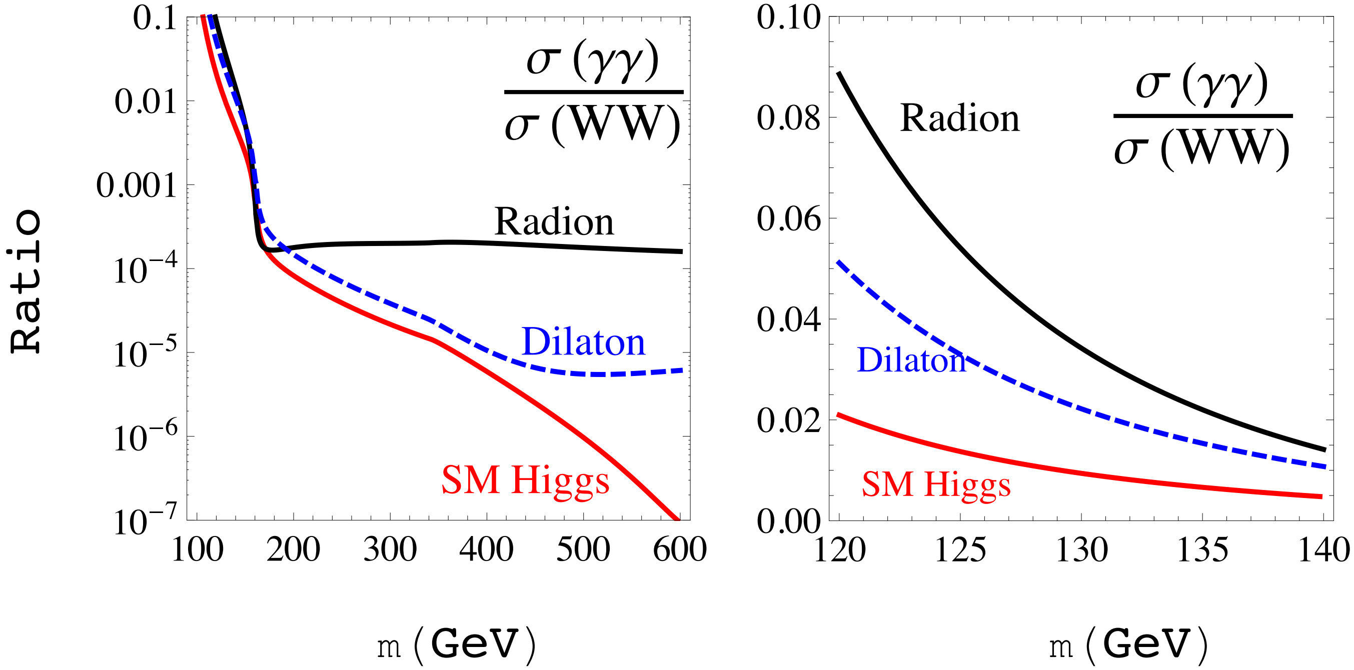
- Dilaton contributes only v^2/f^2 of the "Higgs exchange" amplitude needed to unitarize longitudinal WW scattering:
$\to$ expect additional strong-dynamics effects near TeV scale.

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 Rgg, $R\gamma\gamma$

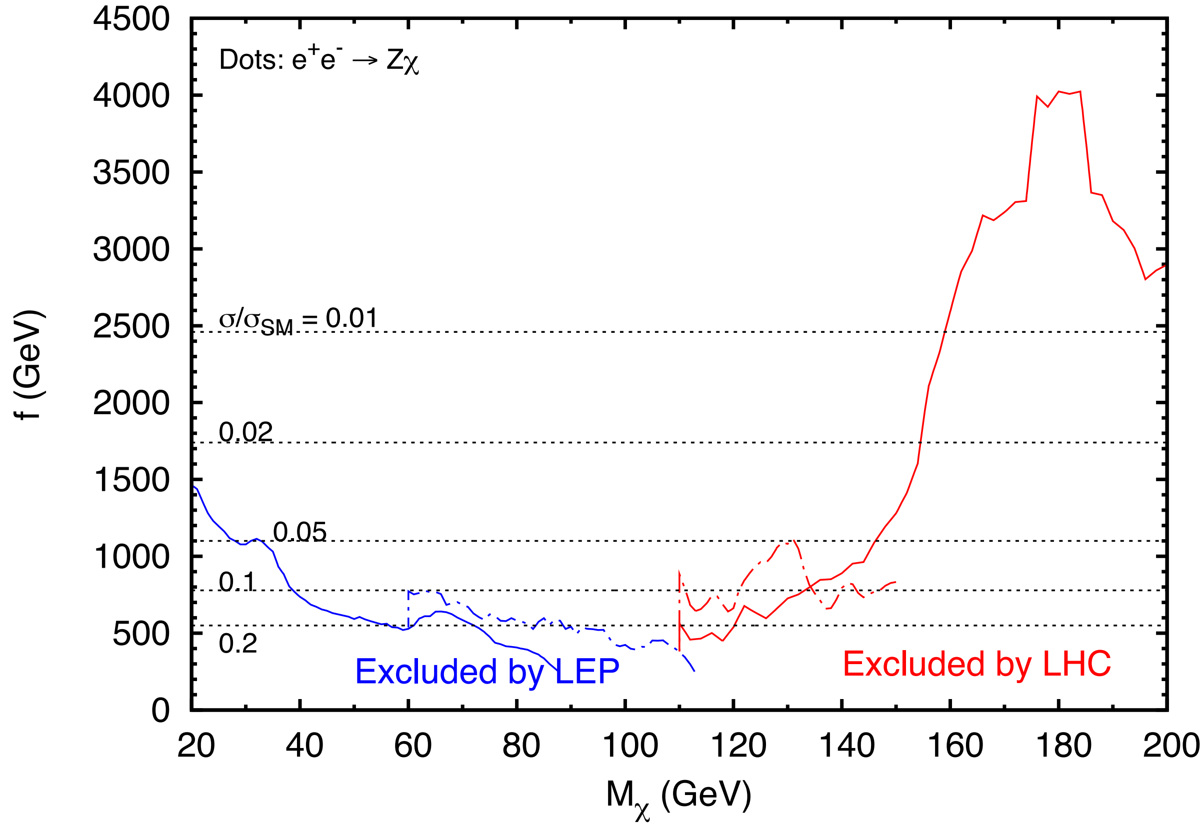
gg, $\gamma\gamma$ couplings $\sim \left[\frac{1}{kL} + \frac{\alpha_{s,\mathrm{EM}}}{2\pi} b_{G,\mathrm{EM}}\right]$, $kL = 35$



Barger, Ishida & Keung, arXiv:1111.4473

ILC prospects: v^2/f^2 cross section suppression hurts a lot

but ILC buys you model-independent measurement of f from $\sigma(e^+e^- \to Z\chi)$ and access to dominant gg decay mode.



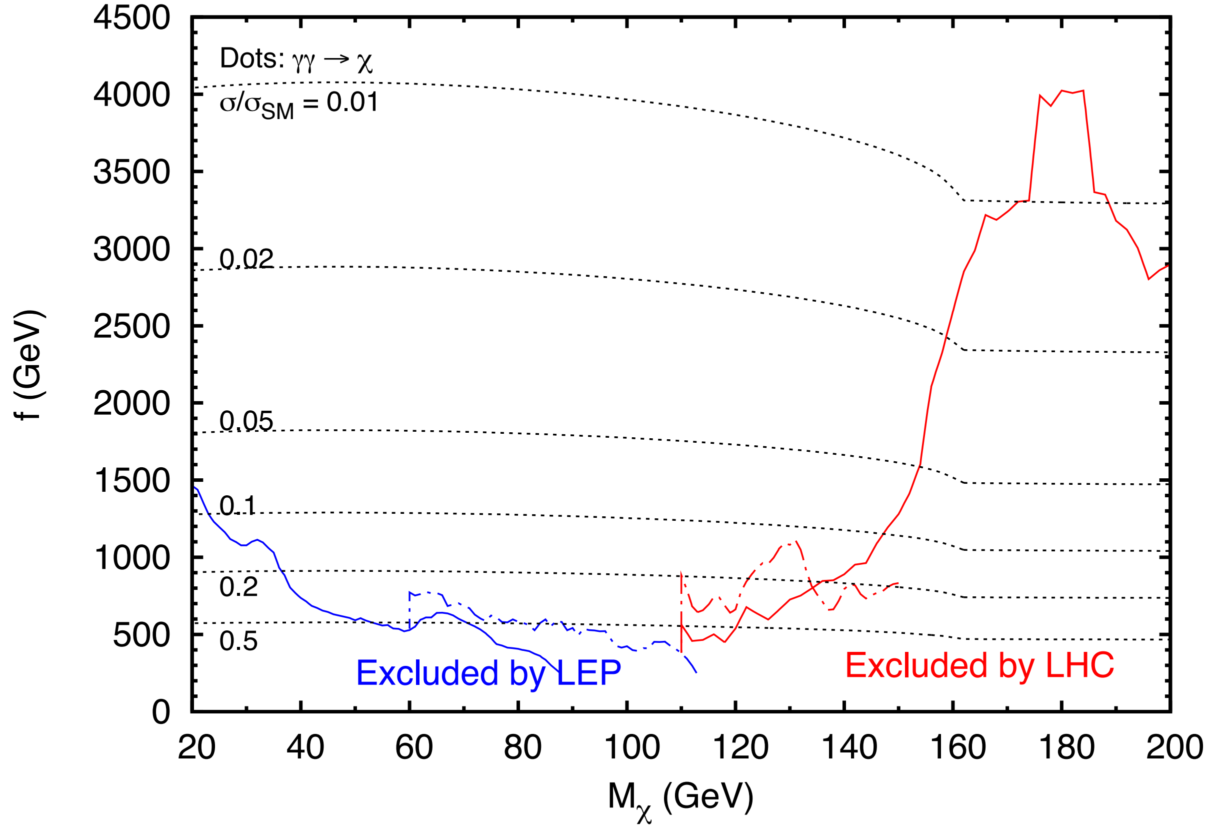
Coleppa, Gregoire & HEL, PRD85, 055001 (2012)

Inclusive $pp \to \chi \to \gamma\gamma$	$2 \times$ SM	$1 \times$ SM
f	886 GeV	1253 GeV
$\sigma(e^+e^- \to Z\chi)$	7.71% $\times$ SM	3.85% $\times$ SM

Photon collider prospects:

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

No decay-mode–independent production rate measurement at PC



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

Inclusive $pp \to \chi \to \gamma\gamma$	$2 \times$ SM	$1 \times$ SM
f	886 GeV	1253 GeV
$\sigma(\gamma\gamma \to \chi)$	18.7% $\times$ SM	9.37% $\times$ SM

More exotic dilaton features: $\chi\chi VV$ couplings

Couplings of the physical dilaton χ 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 χ

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 GeV is consistent with a light dilaton with $f \sim$ 800–1300 GeV.

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