Higgs-dilaton(radion) system confronting the LHC Higgs data

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Introduction

- At last, we have (almost) Higgs boson with 126 GeV?
- Its properties are still waiting to be revealed, really SM or not.
- Still, the data seem to be consistent with the SM.

  $\rightarrow$ Di-Photon and VV enhancement in the ATLAS data.

  $\rightarrow$ other modes?

Introduction

- **Alternatives to the SM**

- **Dilaton as a Higgs imposter :**

  $\rightarrow$ Many models, depending on the hidden conformal sectors. (Grinstein et al.; Barger et al.;Chacko et al.;..)

  $\rightarrow$ Technidilaton, composite Higgs etc. (Yamawaki et al.; D.K. Hong; Csaki et al.;...)

  $\rightarrow$ Radion models from RS, same forms. (P.Ko et al.;Giudice et al.;....)

- **Dilaton(Radion)-Higgs mixing? $\rightarrow$ ....**

DILATON COUPLINGS TO THE SM FIELDS

- **Usual assumption on dilaton couplings to the SM,**

$$\mathcal{L}_{\rm int} \simeq -\frac{\phi}{f_\phi} T^\mu_\mu$$

$$= -\frac{\phi}{f_\phi}\left[2\mu_H^2 H^\dagger H - 2m_W^2 W^+ W^- - m_Z^2 Z_\mu Z^\mu + \sum_f m_f \bar{f} f + \frac{\beta_G}{g_G} G_{\mu\nu} G^{\mu\nu}\right]$$

- **Similar to the SM, except for f_ϕ instead of v.**

- **All–assuming the dilaton coupling to the EW sector "AFTER" EWSB.**
  $\rightarrow$ Classically, Higgs mass parameter is the only scaling -violating term in the SM Lagrangian.

- **Proposal : $T^\mu_\mu \propto \mu^2 H^\dagger H$ + Scale Anomaly.**

Higgs+Dilaton

- **Dilaton only couples to Higgs mass paramter + scale anomaly.**
- **In terms of $\chi \equiv e^{\phi/f_\phi}$, the Lagrangian for SM + dilaton can be written as**

$$
\begin{aligned}
\mathcal{L} = \quad & \mathcal{L}_{\rm SM}(\mu^2 = 0) + \frac{f_\phi^2}{2}\partial_\mu\chi\partial^\mu\chi \\
- \quad & \mu^2\chi^2 H^\dagger H \\
- \quad & \log\left(\frac{\chi}{S(x)}\right)\left\{\frac{\beta_{g_1}(g_1)}{2g_1}B_{\mu\nu}B^{\mu\nu} + \frac{\beta_{g_2}(g_2)}{2g_2}W^i_{\mu\nu}W^{i\mu\nu} + \frac{\beta_{g_3}(g_3)}{2g_3}G^a_{\mu\nu}G^{a\mu\nu}\right\} \\
+ \quad & \log\left(\frac{\chi}{S(x)}\right)\left\{\beta_u\left(\mathbf{Y_u}\right)\bar{Q}_L\tilde{H}u_R + \beta_d\left(\mathbf{Y_u}\right)\bar{Q}_L H d_R + \beta_l\left(\mathbf{Y_u}\right)\bar{l}_L H e_R + H.c.\right\} \\
+ \quad & \log\left(\frac{\chi}{S(x)}\right)\frac{\beta_\lambda(\lambda)}{4}\left(HH^\dagger\right)^2 \\
- \quad & \frac{f_\phi^2 m_\phi^2}{4}\chi^4\left\{\log\chi - \frac{1}{4}\right\}.
\end{aligned}
$$

Potential Analysis

- **Minimizing the extended potential generally gives**

$$\langle H \rangle = (0, v/\sqrt{2})^T, \quad \langle \phi \rangle = \bar{\phi}.$$

- **From tadpole condition for Higgs boson and dilaton,**

$$\begin{aligned} \lambda v^2 &= \mu^2 \mathrm{e}^{2\frac{\bar{\phi}}{f_\phi}}, \\ \mu^2 v^2 &= f_\phi m_\phi^2 \bar{\phi}\ \mathrm{e}^{2\frac{\bar{\phi}}{f_\phi}}. \end{aligned}$$

- **Similar to the singlet extended SM, but the structures are different.**

Mass Formula

- **The Higgs-Dilaton mass matrix becomes**

$$\mathcal{M}^2(h,\phi) = \begin{pmatrix} m^2_{hh} & m^2_{h\phi} \\ m^2_{\phi h} & m^2_{\phi\phi} \end{pmatrix} = \begin{pmatrix} 2\lambda v^2 & -2\frac{\lambda v^3}{f_\phi} \mathrm{e}^{-2\frac{\bar{\phi}}{f_\phi}} \\ -2\frac{\lambda v^3}{f_\phi} \mathrm{e}^{-2\frac{\bar{\phi}}{f_\phi}} & m^2_\phi \mathrm{e}^{2\frac{\bar{\phi}}{f_\phi}} \left(1 + 2\frac{\bar{\phi}}{f_\phi}\right) \end{pmatrix} \equiv \begin{pmatrix} m^2_h & -m^2_h \frac{v}{f_\phi} \mathrm{e}^{-2\frac{\bar{\phi}}{f_\phi}} \\ -m^2_h \frac{v}{f_\phi} \mathrm{e}^{-2\frac{\bar{\phi}}{f_\phi}} & \tilde{m}^2_\phi \mathrm{e}^{2\frac{\bar{\phi}}{f_\phi}} \end{pmatrix}$$

where

$$\tilde{m}^2_\phi = m^2_\phi \left(1 + 2\frac{\bar{\phi}}{f_\phi}\right).$$

- **Mass eigenvalues and mixing angle :**

$$m^2_{H_{1,2}} = \frac{m^2_h + \tilde{m}^2_\phi \mathrm{e}^{2\frac{\bar{\phi}}{f_\phi}} \mp \sqrt{\left(m^2_h - \tilde{m}^2_\phi \mathrm{e}^{2\frac{\bar{\phi}}{f_\phi}}\right)^2 + 4\mathrm{e}^{-4\frac{\bar{\phi}}{f_\phi}} \frac{v^2}{f^2_\phi} m^4_h}}{2}$$

with

$$\tan\alpha = \frac{-m^2_h \frac{v}{f_\phi} \mathrm{e}^{-2\frac{\bar{\phi}}{f_\phi}}}{\tilde{m}^2_\phi \mathrm{e}^{\frac{2\bar{\phi}}{f_\phi}} - m^2_{H_1}}.$$

$$\mathcal{L}(f,\bar{f},H_{i=1,2}) = -\frac{m_f}{v}\bar{f}fh = -\frac{m_f}{v}\bar{f}f(H_1c_\alpha + H_2s_\alpha) \quad cf. \quad -\frac{v}{f_\phi}\frac{\beta_f}{y_f}\frac{m_f}{v}\bar{f}f\phi\, e^{-\bar{\phi}/f_\phi}$$

$$\mathcal{L}(g,g,H_{i=1,2}) = -\frac{e^{-\bar{\phi}/f_\phi}}{f_\phi}\frac{\beta_3(g_3)}{2g_3}G_{\mu\nu}G^{\mu\nu}\phi = -\frac{e^{-\bar{\phi}/f_\phi}}{f_\phi}\frac{\beta_3(g_3)}{2g_3}G_{\mu\nu}G^{\mu\nu}(-H_1s_\alpha + H_2c_\alpha)$$

$$\begin{aligned}\mathcal{L}(W,W,H_{i=1,2}) &= \frac{2m_W^2}{v}W_\mu^+W^{-\mu}h - \frac{e^{-\bar{\phi}/f_\phi}}{f_\phi}\frac{\beta_2(g_2)}{2g_2}W_{\mu\nu}W^{\mu\nu}\phi \\ &= \frac{2m_W^2}{v}W_\mu^+W^{-\mu}(H_1c_\alpha + H_2s_\alpha) - \frac{e^{-\bar{\phi}/f_\phi}}{f_\phi}\frac{\beta_2(g_2)}{2g_2}W_{\mu\nu}W^{\mu\nu}(-H_1s_\alpha + H_2c_\alpha)\end{aligned}$$

$$\begin{aligned}\mathcal{L}(Z,Z,H_{i=1,2}) &= \frac{m_Z^2}{v}Z_\mu Z^\mu h - \frac{e^{-\bar{\phi}/f_\phi}}{f_\phi}\left\{c_W^2\frac{\beta_2(g_2)}{2g_2} + s_W^2\frac{\beta_1(g_1)}{2g_1}\right\}Z_{\mu\nu}Z^{\mu\nu}\phi \\ &= \frac{m_Z^2}{v}Z_\mu Z^\mu(H_1c_\alpha + H_2s_\alpha) - \frac{e^{-\bar{\phi}/f_\phi}}{f_\phi}\left\{c_W^2\frac{\beta_2(g_2)}{2g_2} + s_W^2\frac{\beta_1(g_1)}{2g_1}\right\}Z_{\mu\nu}Z^{\mu\nu}(-H_1s_\alpha + H_2c_\alpha)\end{aligned}$$

$$\begin{aligned}\mathcal{L}(\gamma,\gamma,H_{i=1,2}) &= -\frac{e^{-\bar{\phi}/f_\phi}}{f_\phi}\left\{s_W^2\frac{\beta_2(g_2)}{2g_2} + c_W^2\frac{\beta_1(g_1)}{2g_1}\right\}F_{\mu\nu}F^{\mu\nu}\phi \\ &= -\frac{e^{-\bar{\phi}/f_\phi}}{f_\phi}\left\{s_W^2\frac{\beta_2(g_2)}{2g_2} + c_W^2\frac{\beta_1(g_1)}{2g_1}\right\}F_{\mu\nu}F^{\mu\nu}(-H_1s_\alpha + H_2c_\alpha)\end{aligned}$$

$$\begin{aligned}\mathcal{L}(\gamma,Z,H_{i=1,2}) &= -\frac{e^{-\bar{\phi}/f_\phi}}{f_\phi}2s_Wc_W\left\{\frac{\beta_2(g_2)}{2g_2} - \frac{\beta_1(g_1)}{2g_1}\right\}Z_{\mu\nu}F^{\mu\nu}\phi \\ &= -\frac{e^{-\bar{\phi}/f_\phi}}{f_\phi}2s_Wc_W\left\{\frac{\beta_2(g_2)}{2g_2} - \frac{\beta_1(g_1)}{2g_1}\right\}Z_{\mu\nu}F^{\mu\nu}(-H_1s_\alpha + H_2c_\alpha)\end{aligned}$$

Inputs : f_ϕ and m_ϕ

Decay	Production	μ_i
$\gamma\gamma$	*Combined*	**ATLAS** : $1.65^{-0.3}_{+0.35}$ **CMS** : $0.78^{-0.26}_{+0.28}$
	ggF	**ATLAS** : $1.6^{-0.36}_{+0.42}$
	VBF	**ATLAS** : $1.7^{-0.89}_{+0.94}$
ZZ^*	*Combined*	**ATLAS** : $1.7^{-0.4}_{+0.5}$ **CMS** : $0.93^{-0.25}_{+0.29}$
	ggF	**ATLAS** : $1.8^{-0.5}_{+0.8}$ **CMS** : $0.8^{-0.36}_{+0.46}$
	VBF(VH)	**ATLAS** : $1.2^{-1.4}_{+3.8}$ **CMS** : $1.7^{-2.1}_{+2.2}$
WW^*	*Combined*	**ATLAS** : $1.01^{-0.31}_{+0.31}$ **CMS** : $0.72^{-0.18}_{+0.2}$
bb	*VH*	**ATLAS** : $0.2^{-0.7}_{+0.7}$ **CMS** : $1.0^{-0.5}_{+0.5}$
$\tau\tau$	*Combined*	**ATLAS** : $1.4^{-0.4}_{+0.5}$ **CMS** : $1.1^{-0.4}_{+0.4}$

- **Constraints for the signal strenths from the LHC,**
- **3-σ bounds around χ^2 minima of ATLAS OR CMS data assinged.**
- **Experimental constraints for heavy/light Higgs bosons from LEP/LHC exp.**

$$m_{H_1} = 126 \text{ GeV},$$

$$+$$

heavy scalar.

$(m_{H2} > m_{H1} = 126\text{GeV})$

- **Allowed range is highly constrained-coincides with SM results.**
- **Precise Heavy scalar boson phenomenology is required.**

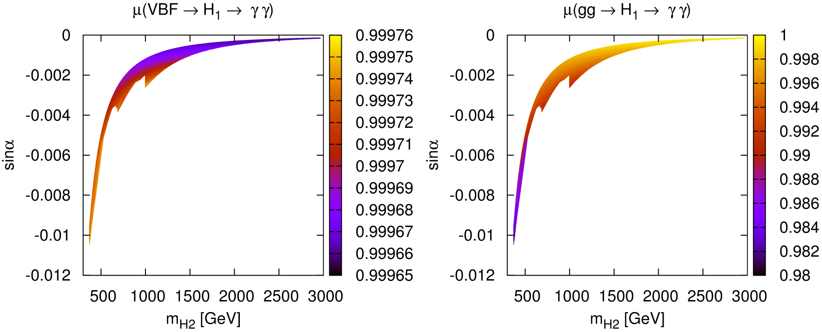

Figure: Rates relative to the SM values: ggF and VBF

$$m_{H_2} = 126 \text{ GeV},$$

$$+$$

light scalar.

($m_{H1} < m_{H2} = 126\text{GeV}$)

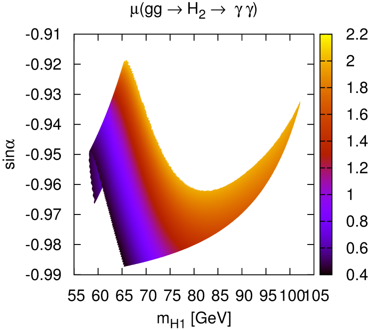

Figure: Rates relative to the SM values: ggF and VBF

Typical prediction I

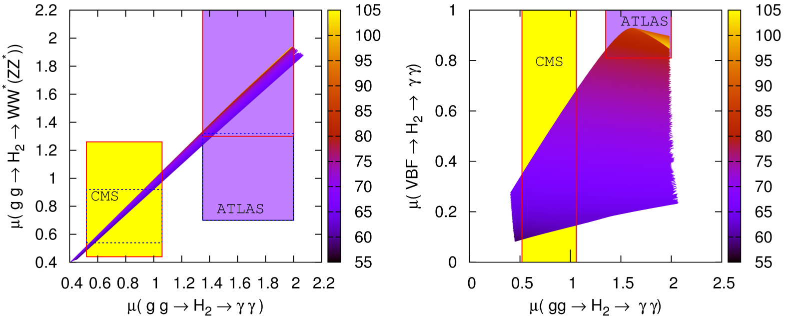

Figure: Correlations, diphoton vs. $WW^*(ZZ^*)$ (left) and ggF vs VBF(right).

Typical prediction II

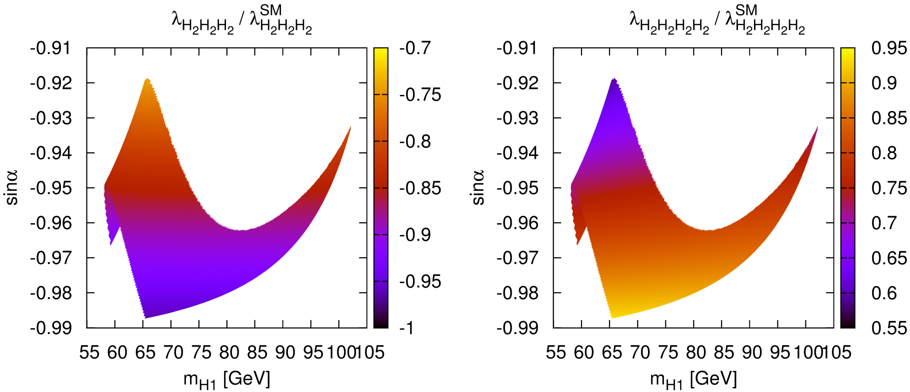

Figure: Triple and Quartic couplings.

More possible distinctions?

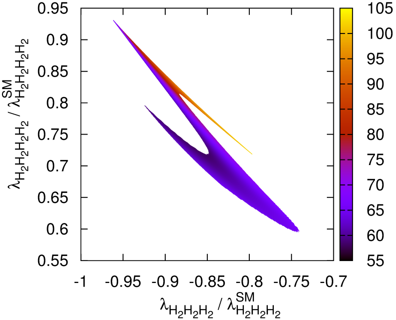

Figure: correlation, triple and quartic couplings

Summary and Prospects

- **We consider NEW Higgs-Dilaton mixing scenario, which occours before EWSB.**
- **Can be fit.**
- **Generically, scale anomaly contribution is not neglibile, especailly for gg couplings.**
- **Extra heavy scalar scenario $\rightarrow$ hard to probe.**
- **Extra light scalar scenario $\rightarrow$ rich phenomenologies, in cluding many distinctive predictions.**

Summary and Prospect

- More works on,
  - detailed heavy (light) Higgs phenomenology,
  - Higgs pair production or invisible decay of Higgs?
  - EW precision test?
  - Related DM study..?
  - etc.,etc....