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 :**

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

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

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

- **Dilaton(Radion)-Higgs mixing? →**

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

- **Higgs can be lighter that scale symmetry breaking scale or 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,**

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

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

Mass Formula

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

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

where

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

- **Mass eigenvalues and mixing angle :**

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

with

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

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

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

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

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

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

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

Numerical Results

- **Inputs : f_ϕ and m_ϕ ($m_h = 126$GeV, α and $m_H(> m_h)$ are calculated.)**

Decay	Production	R_i
WW^*	*combined*	**ATLAS-CONF-2013-030 : 1.01 -0.31 +0.31** **CMS-HIG-13-003 : 0.76 -0.21 +0.21**
ZZ^*	*combined*	**ATLAS-CONF-2013-013 : 1.7 -0.4 +0.5** **CMS-HIG-13-002 : 0.91 -0.24 +0.3**
	VBF(+VH for ATLAS)	**ATLAS-CONF-2013-013 : 1.2 -1.4 +3.8** **CMS-HIG-13-002 : 1 -2.3 + 2.4**
	fermion	**ATLAS-CONF-2013-013 : 1.8 -0.5 +0.8** **CMS-HIG-13-002 : 0.9 -0.4 + 0.5**
$\gamma\gamma$	*combined*	**ATLAS-CONF-2013-012 : 1.65 -0.3 +0.35** **CMS-HIG-13-001 : 0.78 -0.26 +0.28**
	VBF	**ATLAS-CONF-2013-012 : 1.7 -0.89 +0.94**
	fermion	**ATLAS-CONF-2013-012 : 1.6 -0.36 +0.42**
$b\bar{b}$	*W/Zassociated*	**ATLAS-CONF-2012-161 : -0.4 -1.06 + 1.06** **CMS-HIG-12-044 : 1.3 -0.6 +0.7**
$\tau\bar{\tau}$	*combined*	**ATLAS-CONF-2013-160 : 0.7 -0.7 +0.7** **CMS-HIG-13-044 : 1.1 -0.4 +0.4**

χ^2 analysis

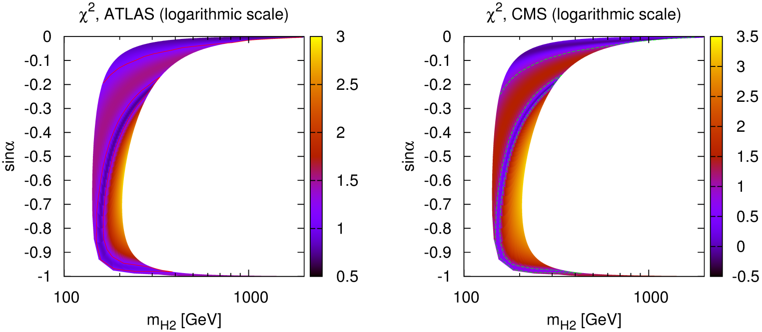

Figure: χ^2 plots for the ATLAS and CMS cases.

Rate:gluon Fusion and VBF processes

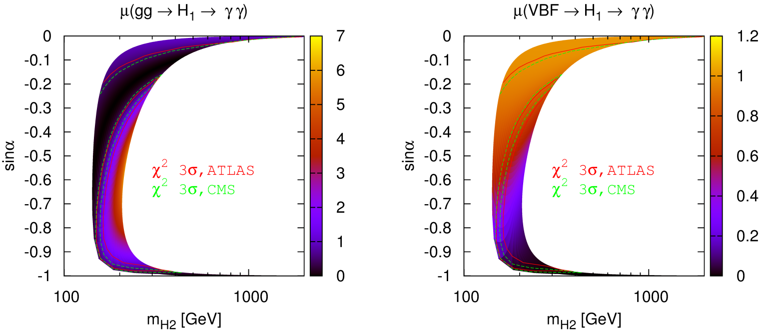

Figure: Rates relative to the SM values: ggF and VBF

Typical prediction I

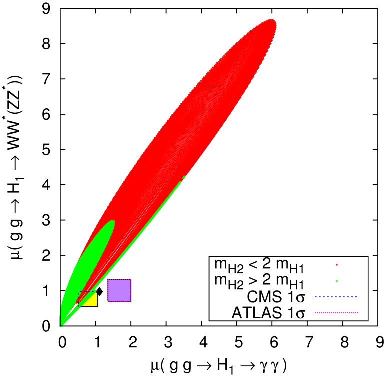

Figure: Correlations, diphoton vs. $WW^*(ZZ^*)$.

Typical prediction II

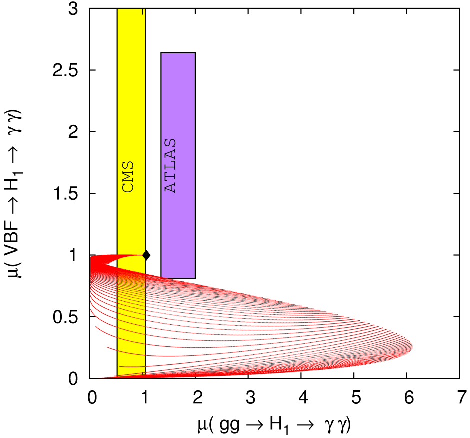

Figure: Correlation between *gg* and VBF

More possible distinctions?

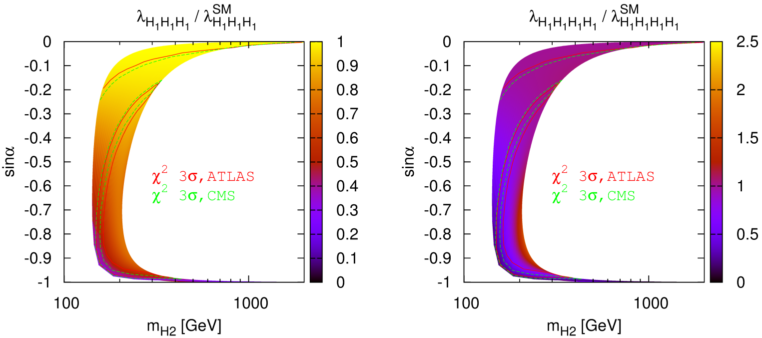

Figure: Triple and quartic Higgs couplings relative to the SM values.

Summary and Prospects

- **We consider NEW Higgs-Dilaton mixing scenario, which occours before EWSB.**
- **'Can' be fit with the data until now.**
- **Generically, more modification on the gg initiated process and mixing angle suppression for other process.**
- **The study of the case that Heavy Higgs is observed 126 boson is under way. The light Higgs phenomenology is not trivial and more interesting.**
- **If things are going well,**
  - **Heavy(light) Higgs phenomenology?**
  - **Higgs pair production or invisible decay of Higgs?**