Higgs-Dilaton/Radion System @LHC

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Introduction, a la '*Aspects of Symmetry*'

- **Dilaton = Goldstone boson of scale transforamtion.**
- $\alpha : x \to e^{\alpha} x$.
- $\alpha : \phi(x) \to e^{\alpha d} \phi(e^{\alpha x})$.
- **Infinitesimal transf.** $\delta\phi = (d + x^{\lambda}\partial_{\lambda})\phi$.
- **Symmetry, if no dimensionful couplings.**

Introduction

- **example :** $\mathcal{L} = \mathcal{L}_S + \mathcal{L}_B$,

- $\mathcal{L}_S = i\bar{\psi}\gamma_\mu\partial^\mu\psi + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + g\bar{\psi}\gamma_5\psi\phi - \frac{\lambda}{4!}\phi^4$.
- $\mathcal{L}_B = -m\bar{\psi}\psi - \frac{1}{2}\mu^2\phi^2$.

- $\delta\psi = (\frac{3}{2} + x_\lambda\partial^\lambda)\psi, \quad \delta\phi = (4 + x_\lambda\partial^\mu)\phi$.

- **It follows that**
  $\delta\mathcal{L}_S = (4 + x_\lambda\partial^\lambda)\mathcal{L}_S$,
  $\delta\mathcal{L}_B = -(3 + x_\lambda\partial^\mu)m\bar{\psi}\psi - \frac{1}{2}(2 - x_\lambda\partial^\lambda)\mu^2\phi^2$.

- **Integrating by parts,** $\Delta = m\bar{\psi}\psi + \mu^2\phi^2$.

- **Scale current** $\partial_\mu s^\mu = \Delta, \quad s^\mu = x_\nu\theta^{\mu\nu}$.

Hidden Scale Invariance

- **Non-linear realization**

  $\alpha : \chi(x) \to e^{\alpha}\chi(e^{\alpha}x),$

  and define a new field σ**, by** $fe^{\sigma/f} = \chi.$

- **Transf.** $\alpha : \sigma(x) \to \sigma(e^{\alpha}x) + \alpha f. \to \delta\sigma = x^{\lambda}\partial_{\lambda}\sigma + f.$ **cf. pion.**

- **scale invariant Lag. for** σ**,**

  $\mathcal{L} = \frac{1}{2}\partial_{\mu}\chi\partial^{\mu}\chi = \frac{f^2}{2}\partial_{\mu}(e^{\sigma/f})\partial^{\mu}(e^{\sigma/f}).$

Hidden Scale Invariance

- **Using σ field, the scale invaraint Lag,**

$$\mathcal{L} = \mathcal{L}_S - m\bar{\psi}\psi e^{\sigma/f} - \frac{\mu^2}{2}\phi^2 e^{2\sigma/f} + \frac{f^2}{2}\partial_\mu(e^{\sigma/f})\partial^\mu(e^{\sigma/f}).$$

- **PCDC (analogy of PCAC) symmetry breaking term,**

$$\mathcal{L}_B = -\frac{f^2 m_\sigma^2}{16}(e^{4\sigma/f} - 4\sigma/f - 1).$$

- $\delta\mathcal{L}_B = x_\lambda \partial^\lambda \mathcal{L}_B - \frac{f^2 m_\sigma^2}{16}(4e^{f\sigma/f} - 4).$
- $\partial_\mu s^\mu = \theta^\mu_\mu = -f m_\sigma^2 \sigma..$

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**

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

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**

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

where

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

- **Mass eigenvalues and mixing angle :**

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

with

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

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

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

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

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

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

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

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** : $1.1^{-0.4}_{+0.4}$

TABLE : Signal strengths reported by ATLAS and CMS.

- **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.

Typical behavior on the parameter space

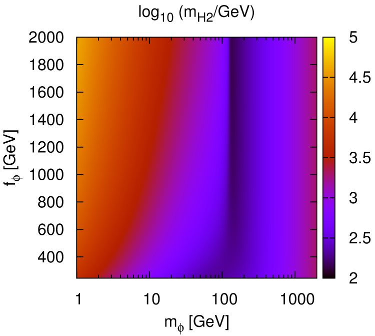

Figure : Contour plots for the mixing angle and extra light boson mass in the (m_ϕ, f_ϕ) plane.

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

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

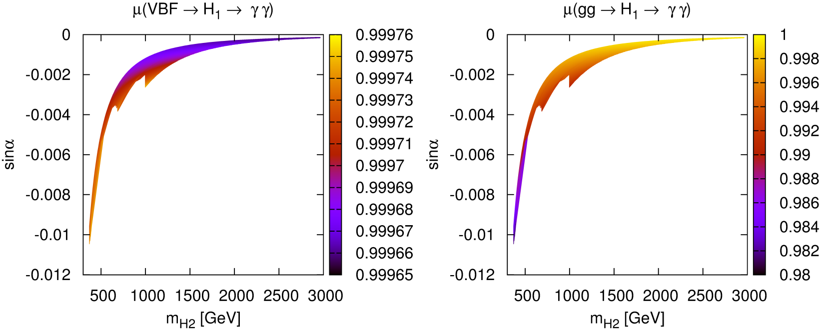

FIGURE : Rates relative to the SM values: ggF and VBF

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

$$+$$

light scalar.

Typical behavior on the parameter space

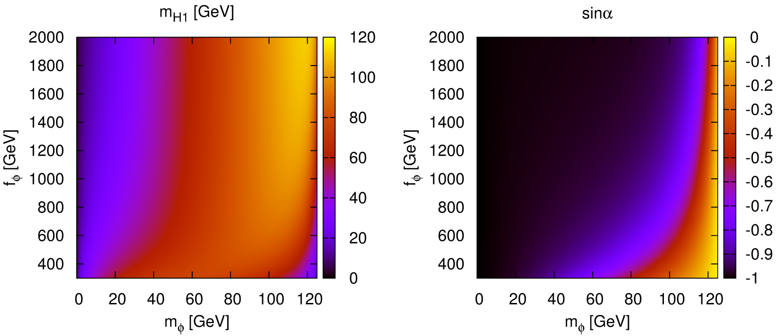

Figure : Contour plots for the mixing angle and extra light boson mass in the (m_ϕ, f_ϕ) plane.

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

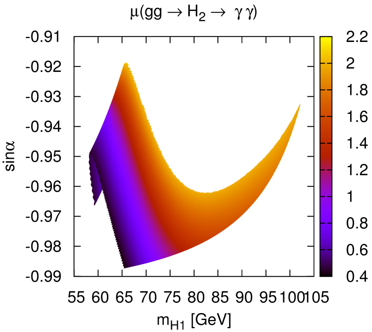

FIGURE : Rates relative to the SM values: ggF and VBF

Typical prediction I

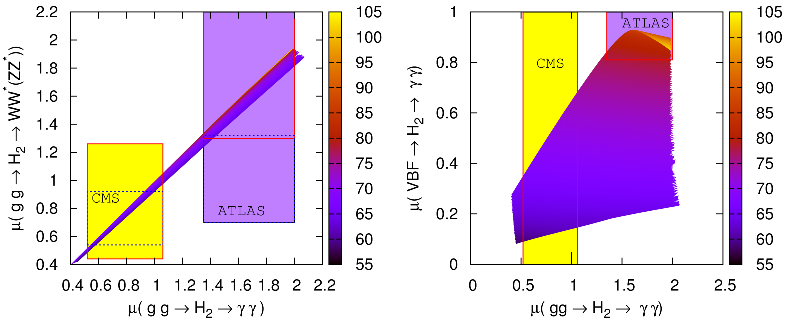

Figure : Correlations, diphoton vs. $WW^*(ZZ^*)$ (left) and ggF vs VBF(right).

Typical prediction II

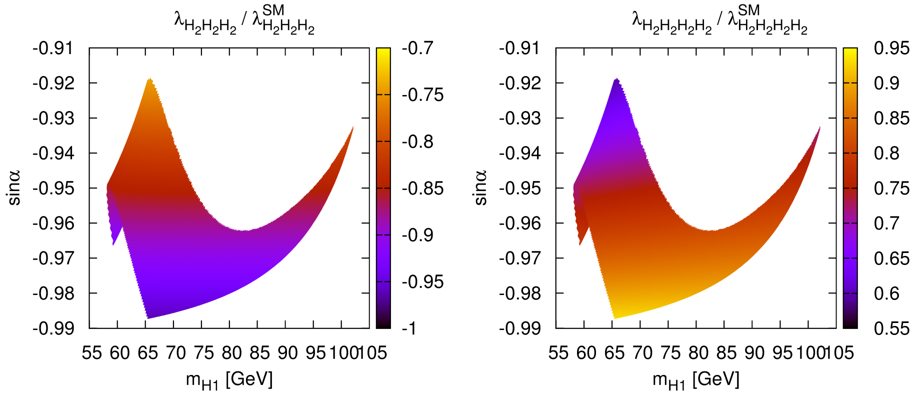

Figure : Triple and Quartic couplings.

More possible distinctions?

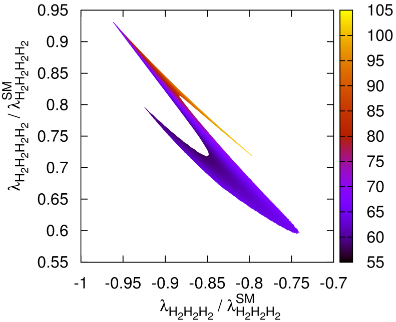

Figure : correlation, triple and quartic couplings

OUTLOOK

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

Outlook

- **Different from usual RS setup (see Prof. Csaki's work) : By escaling $H \to \Omega_b^{-1} H$ and $\psi \to \Omega_b^{-3/2}\psi$,**

$$
\begin{aligned}
S_{eff} &= \int d^4x\sqrt{g}\left(g^{\mu\nu} D_\mu H^\dagger D_\nu H - V(H,\phi) + i\bar{\psi}_i e^{a\mu}\gamma_a D_\mu \psi_i - \lambda_{ij} H\psi_i\psi_j + h.c.\right) \\
&\quad + S_{radion} + \int d^4x\sqrt{g}\left(\frac{1}{\sqrt{6}}\frac{\partial\phi}{\Lambda_W}\left(H^\dagger DH + h.c.\right) + \left(\frac{\partial\phi}{\sqrt{6}\Lambda_W}\right)^2 H^\dagger H\right) \\
&\quad + \int d^4x\sqrt{g}\left(\frac{3}{2\sqrt{6}\Lambda_W} i\bar{\psi}_i\gamma^\mu\psi\partial_\mu\phi\right) + S_{Pl}\ .
\end{aligned}
$$

$\to$ **Kinetic mixing can be removed by suitable rotation, but in that case radion couples to the various terms because of radion-Higgs mixing.**

- **Finding out new setup?**
- **AdS/CFT interpretation on the dilaton/radion and their matching? .....**