Couplings and width of the Higgs (-like) particle

Bogdan Dobrescu (Fermilab)

Outline:
- General Higgs couplings
- Upper & lower limits on the Higgs width and couplings
- Non-standard production and decays

Work with Joe Lykken: 1210.3342

Theory Seminar - UC Davis, April 15, 2013
A Higgs boson is defined as any scalar particle $h^0$ that couples to the $W$ and $Z$ according to:

$$
\frac{h^0}{v_h} \left( 2\kappa_W M_W^2 W^+_\mu W^-\mu + \kappa_Z M_Z^2 Z_\mu Z^\mu \right)
$$

$v_h \approx 246 \text{ GeV}$

Couplings of a Higgs boson to 3rd generation fermions:

$$
-\frac{h^0}{v_h} \left( \kappa_t m_t \bar{t}t + \kappa_b m_b \bar{b}b + \kappa_\tau m_\tau \bar{\tau}\tau \right)
$$

$\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau$ are real parameters, equal to 1 in the SM.
Effective Higgs coupling to a pair of gluons is given by a dimension-5 operator:

\[ \kappa_g \frac{\alpha_s}{12\pi v} h^0 G^{\mu\nu} G_{\mu\nu} \]

Effective coupling to photons:

\[ \kappa_\gamma \equiv \left( \frac{\Gamma(h^0 \to \gamma\gamma)}{\Gamma_{SM}(h^0 \to \gamma\gamma)} \right)^{1/2} \]

Within the SM: \( \kappa_g = \kappa_\gamma = 1 \). Deviations from 1 are due to new particles in the loops as well as changes in the Higgs couplings to \( \bar{t}t \) and \( WW \).

Couplings of a non-standard Higgs boson are described by 7 parameters: \( \kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_g, \kappa_\gamma \).

Eventually, \( \kappa_{Z\gamma} \) and \( \kappa_\mu \) will also be important (also \( h \to \tau\mu, \ldots \))

Harnik et al, 1209.1397)
Importance of the total width

Cross section × branching fractions for $\Gamma_h \ll M_h$:

$$\sigma(pp \rightarrow h + X \rightarrow ... + X) \propto \frac{1}{\Gamma_h}$$

$\Gamma_{h}^{\text{SM}}/M_h \approx 3.2 \times 10^{-5}$ for $M_h = 126$ GeV.

Rate measurements give: $\frac{\kappa_{\text{prod.}}^2 \kappa_{\text{decay}}^2}{\Gamma_h}$

Higgs couplings $\kappa_P$ cannot be extracted from LHC data, in the absence of some theoretical assumptions, because an increase in all couplings can be compensated by a larger $\Gamma_h$ due to (almost) undetectable decays through new particles.
\[ g t \rightarrow h^0 \]

**CMS:** \( M_h = 125.8 \pm 0.5 \text{ GeV} \)

**ATLAS:** \( M_h = 124.3 \pm 0.7 \text{ GeV} \)

Current resolution (\( \sim 1 \text{ GeV} \)) implies

\[ \frac{\Gamma_h}{\Gamma_{SM}} \lesssim 10^2 \]
Our method (1210.3342):

1. Define the “apparent squared couplings”:

\[ a_\mathcal{P} = \kappa_\mathcal{P}^2 \left( \frac{\Gamma_{\text{SM}}}{\Gamma_h} \right)^{1/2} \]

for \( \mathcal{P} = W, Z, g, \gamma, t, b, \tau \)

\( a_\mathcal{P} \) can be extracted directly from the CMS and ATLAS data:

\[ \text{Rate} = a_{\text{prod}} \cdot a_{\text{decay}} \]

2. Based on some theoretical assumption, the couplings \( \kappa_\mathcal{P} \) (Lagrangian parameters!) can then be related to \( a_\mathcal{P} \).


- no decays into non-SM particles, or some \( \kappa_\mathcal{P} = 1 \).

A well-motivated assumption: an upper limit on \( \kappa_W \) or \( \kappa_Z \).
First, extract the $a_P$ observables from the rate measurements:

\[
\begin{align*}
\left( \frac{\sigma}{\sigma_{\text{SM}}} \right) (hjj \rightarrow \gamma\gammajj) &= \frac{a_W + r a_Z}{1 + r} a_{\gamma} \\
r &\approx 0.3
\end{align*}
\]

\[
\left( \frac{\sigma}{\sigma_{\text{SM}}} \right) (Wh \rightarrow Wb\bar{b}) = a_W a_b
\]
Contamination of “VBF tagged” sample from the gluon fusion (+ jj) channel:

\[ a_{\text{VBF}} \approx (1 - f_g) \frac{a_W + r a_Z}{1 + r} + f_g a_g \]

SM simulations: \( f_g \approx 30\% \) (20\% - 50\% depending on event selection)

Contamination of gluon fusion from VBF is small (\( \sim 10\% \)).
<table>
<thead>
<tr>
<th>$h^0$ decay</th>
<th>$h^0$ production</th>
<th>observable</th>
<th>measured $\sigma/\sigma_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW^*$</td>
<td>$gg \rightarrow h^0$</td>
<td>$a_g a_W$</td>
<td>$0.8 \pm 0.4$, <strong>ATLAS</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$0.76 \pm 0.21$, <strong>CMS</strong></td>
</tr>
<tr>
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<td></td>
<td></td>
<td>$0.94^{+0.85}_{-0.83}$, <strong>Tevatron</strong></td>
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<td></td>
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<td></td>
<td><strong>our average</strong>: $0.78 \pm 0.18$</td>
</tr>
<tr>
<td>$VBF$</td>
<td></td>
<td>$a_{VBF} a_W$</td>
<td>$1.7 \pm 0.8$, <strong>ATLAS</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$-0.05^{+0.74}_{-0.55}$, <strong>CMS</strong></td>
</tr>
<tr>
<td>$W^* \rightarrow Wh^0$</td>
<td>$a_W^2$</td>
<td></td>
<td>$-0.3^{+2.2}_{-1.9}$, <strong>CMS</strong></td>
</tr>
<tr>
<td>$Z^* \rightarrow Zh^0$</td>
<td>$a_Z a_W$</td>
<td></td>
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</tr>
<tr>
<td>$ZZ^*$</td>
<td>$gg \rightarrow h^0$</td>
<td>$a_g a_Z$</td>
<td>$1.5 \pm 0.4$, <strong>ATLAS</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$0.9^{+0.5}_{-0.4}$, <strong>CMS</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>our average</strong>: $1.3 \pm 0.3$</td>
</tr>
<tr>
<td>$VBF$</td>
<td></td>
<td>$a_{VBF} a_Z$</td>
<td>$1.0^{+2.4}_{-2.3}$, <strong>CMS</strong></td>
</tr>
</tbody>
</table>

*Note: The measured values are for the ratio of the process's rate to the Standard Model prediction $\sigma$, with uncertainties and *labels.*
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<th>measured $\sigma/\sigma_{SM}$</th>
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</thead>
</table>
| $\gamma\gamma$ | $gg \rightarrow h^0$ | $a_g a_\gamma$ | $1.6^{+0.5}_{-0.4}$, ATLAS  
$0.5^{+0.6}_{-0.4}$, CMS  
$6.0^{+3.4}_{-3.1}$, Tevatron  
our average: $1.4 \pm 0.4$ |
| VBF | $a_{VBF} a_\gamma$ | $1.7^{+1.0}_{-0.8}$, ATLAS  
$1.5 \pm 1.1$, CMS  
our average: $1.6^{+0.7}_{-0.6}$ |
| $W^* \rightarrow Wh^0$ | $a_W a_\gamma$ | $1.8 \pm 1.4$, ATLAS |
| $Z^* \rightarrow Zh^0$ | $a_Z a_\gamma$ | |

*Note: $\gamma\gamma$ production and measured values are from a specific context.
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<td>$\bar{b}b$</td>
<td>$W^* \rightarrow Wh^0$</td>
<td>$a_W a_b$</td>
<td>$-0.4 \pm 1.0$, ATLAS</td>
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<td>$1.31^{+0.65}_{-0.60}$, CMS</td>
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<tr>
<td></td>
<td>$Z^* \rightarrow Zh^0$</td>
<td>$a_Z a_b$</td>
<td>$1.59^{+0.69}_{-0.72}$, Tevatron</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t}h^0$</td>
<td>$a_t a_b$</td>
<td>$-0.80^{+2.10}_{-1.84}$, CMS</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>$gg \rightarrow h^0$</td>
<td>$a_g a_\tau$</td>
<td>$2.4 \pm 1.7$, ATLAS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$0.8^{+0.5}_{-0.6}$, CMS</td>
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<td>our average: $1.0^{+0.4}_{-0.5}$</td>
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<td>$W^* \rightarrow Wh^0$</td>
<td>$a_W a_\tau$</td>
<td>$-0.4 \pm 1.2$, ATLAS</td>
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<td></td>
<td></td>
<td></td>
<td>$1.4 \pm 0.6$, CMS</td>
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<tr>
<td></td>
<td>$Z^* \rightarrow Zh^0$</td>
<td>$a_Z a_\tau$</td>
<td>$?$, ATLAS</td>
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<td>$0.8 \pm 1.5$, CMS</td>
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</table>
Electroweak data requires $\kappa_W/\kappa_Z = 1 \pm O(10^{-2})$
(unless some BSM contributions are tuned to cancel the effects of $h^0$)

For simplicity, assume $\kappa_W = \kappa_Z \equiv \kappa_V$.

Combine the $gg \rightarrow h^0 \rightarrow WW^*, ZZ^*$ rate measurements:

$$a_g a_V = \left(\frac{\sigma}{\sigma_{SM}}\right)(gg \rightarrow h \rightarrow VV^*) = 0.92 \pm 0.15$$

Using measurements for $a_g a_V$, $a_g a_\gamma$, $a_{VBF} a_\gamma$:

$$a_V^2 = \left(\frac{\sigma}{\sigma_{SM}}\right)(gg \rightarrow h \rightarrow VV^*)\frac{\left(\frac{\sigma}{\sigma_{SM}}\right)(VBF \rightarrow hjj \rightarrow \gamma\gammajj)}{\left(\frac{\sigma}{\sigma_{SM}}\right)(gg \rightarrow h \rightarrow \gamma\gamma)}$$

for $f_g = 0$.

Using (bifurcated) Gaussian distributions,

$$a_V = 1.00^{+0.34}_{-0.22}$$

Similarly, extract $a_g$, $a_\gamma$. Measurements for $a_V a_b$, $a_g a_\tau$ give $a_b$ and $a_\tau$. 
\[ a_P = \kappa_P^2 \left( \frac{\Gamma_{SM}}{\Gamma_h} \right)^{1/2} \]

Intervals for ‘apparent squared-couplings’:

for \( f_g = 0 \), and including the VBF data only for \( h^0 \rightarrow \gamma\gamma \).
A lower limit on $\Gamma_h$ can be derived from the rates required for its observation.

$$\Gamma_h = \sum_{\mathcal{P} = W, Z, b, \tau, g, \gamma} \kappa_{\mathcal{P}}^2 \Gamma^{SM}(h^0 \rightarrow \mathcal{P}\mathcal{P}) + \Gamma_X$$

$\Gamma_X$ is the $h^0$ partial decay width into final states other than the SM ones.

Given that $\Gamma_X \geq 0$,

$$\Gamma_h \geq \Gamma_h^{\text{min}} = \left( \sum_{\mathcal{P} = W, Z, b, \tau, g, \gamma} a_{\mathcal{P}} B^{SM}(h^0 \rightarrow \mathcal{P}\mathcal{P}) \right)^2 \Gamma_h^{SM}$$

Lower limit on the width:

$$\Gamma_h \geq \Gamma_h^{\text{min}} = 0.90^{+0.78}_{-0.25} \Gamma_h^{SM}$$
If electroweak symmetry breaking is due entirely to VEVs of $SU(2)_W$ doublets, then:

$$0 < \kappa_W = \kappa_Z \leq 1$$

If triplets or higher $SU(2)_W$ representations acquire VEVs, it is possible to have $\kappa_W \neq \kappa_Z$, and values for $\kappa_W, \kappa_Z > 1$.

Even then one can derive some upper bounds ($\sim 1.5$) on the couplings:

$$|\kappa_W| < \kappa_W^{\text{max}}, \quad |\kappa_Z| < \kappa_Z^{\text{max}}$$

*Can be directly tested at the LHC through searches for $H^{++}$, ...*
The upper limits on $\kappa_W$ and $\kappa_Z$ imply

$$\Gamma_h \leq \Gamma_h^{\text{max}} = \text{Min} \left\{ \frac{(\kappa_W^{\text{max}})^4}{a_W^2}, \frac{(\kappa_Z^{\text{max}})^4}{a_Z^2} \right\} \Gamma_h^{\text{SM}}$$

If the electroweak symmetry is broken only by the VEVs of $SU(2)_W$ doublets (majority of viable theories), then

$$\Gamma_h \leq \Gamma_h^{\text{max}} = \frac{\Gamma_h^{\text{SM}}}{a_V^2}$$

$a_V$ extracted from the current data gives:

$$\Gamma_h \leq \Gamma_h^{\text{max}} = 0.71^{+0.93}_{-0.15} \Gamma_h^{\text{SM}}$$
\[ a_{\mathcal{P}}^{1/2} \left( \frac{\Gamma_{\text{min}}}{\Gamma_{h}^{\text{SM}}} \right)^{1/4} < \kappa_{\mathcal{P}} < a_{\mathcal{P}}^{1/2} \left( \frac{\Gamma_{\text{max}}}{\Gamma_{h}^{\text{SM}}} \right)^{1/4} \]

**Coupling ‘spans’:**

updated in April 2013, based on Dobrescu, Lykken: 1210.3342
Branching fraction of exotic decays:

(non-SM particles, $c\bar{c}$, ...)

$$B_X = 1 - \frac{1}{\Gamma_h} \sum_{\mathcal{P} = W, Z, b, \tau, g, \gamma} \kappa_\mathcal{P}^2 \Gamma_{\text{SM}}(h^0 \to \mathcal{P}\mathcal{P})$$

$$\Rightarrow B_X \leq B_{X}^{\text{max}} = 1 - \left( \frac{\Gamma_{h}^{\text{SM}}}{\Gamma_{h}^{\text{max}}} \right)^{1/2} \sum_{\mathcal{P} = W, Z, b, \tau, g, \gamma} a_\mathcal{P} B_{\text{SM}}(h^0 \to \mathcal{P}\mathcal{P})$$

$$B_{X}^{\text{max}} < 22\% \text{ at the 68\% CL}$$

$$B_{X}^{\text{max}} < 46\% \text{ at the 95\% CL}.$$
Non-standard Higgs production

Standard-Model gluon fusion $\pm$ non-standard contributions

Higgs ‘portal’ coupling: $\lambda_G G_H^a G_H^a H^\dagger H$, $G_H$ has spin 0, carries color.

The direct signatures of the new colored particles at the LHC may have large backgrounds.
Scalar octet

$G_H$: spin 0, transforms as $(8,1,0)$ under $SU(3)_c \times SU(2)_W \times U(1)_Y$

$SU(2)_W$ forbids renormalizable couplings of $G_H$ to SM quarks.

Renormalizable couplings of $G_H$ to gluons are fixed by $SU(3)_c$ gauge invariance

$\Rightarrow$ production of $G_H$ at hadron colliders occurs in pairs.

$G_H$ decays are model dependent.

**A simple possibility:** $G_H \rightarrow gg$

Dobrescu, Bai, 1012.5814

**A more complicated decay:** $G_H \rightarrow \bar{\psi}^* \psi^* \rightarrow g\bar{q}gq$

Dobrescu, Kong, Mahbubani, hep-ph/0709.2378
Signal: a pair of narrow $gg$ resonances of same mass

$$\begin{align*}
g &\rightarrow GG_H \rightarrow gggg \\
g &\rightarrow GG_H \rightarrow gggg
\end{align*}$$

$200 \leq M_{GH} [\text{GeV}] \leq 800$

$\Sigma [\text{pb}]$

$\int \mathcal{L} = 2.2 \text{ fb}^{-1}$

$\int \mathcal{L} = 4.6 \text{ fb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}$

CMS Preliminary

ATLAS search for $(jj)(jj)$
For $M_h^2 \ll M_{GH}^2$: \( \kappa_g \approx 1 + 3\lambda_G \frac{v_h^2}{8M_{GH}^2} \)

Change in Higgs production through gluon fusion:

\[
\frac{\sigma(pp \to h)/\sigma(pp \to h)_{SM}}{\Delta\sigma(pp \to h)/\Delta\sigma(pp \to h)_{SM}}
\]

- $M_G = 250$ GeV
- $M_G = 400$ GeV

Dobrescu, Kribs, Martin: 1112.2208

(see also Bai, Fang, Hewett 1112.1964; Kumar, Vega-Morales, Yu 1205.4244)
Nonstandard Higgs decays

Standard model + a gauge-singlet complex scalar $S$:

$$S = \frac{1}{\sqrt{2}} (\varphi_S + \langle S \rangle) e^{iA^0/\langle S \rangle}$$

$A^0$ is a CP-odd spin-0 particle

$$\frac{c v}{2} h^0 A^0 A^0 \text{ coupling} \Rightarrow \Gamma(h^0 \rightarrow A^0 A^0) = \frac{c^2 v^2}{32\pi M_h} \left(1 - 4 \frac{M_A^2}{M_h^2}\right)^{1/2}$$

For $2M_A \ll M_h = 125$ GeV:

Higgs boson may be the portal to a hidden sector: dark matter, ...
$A^0$ decays are model dependent.

Example: \cite{Dobrescu,Landsberg,Matchev,hep-ph/0005308}

Even $\mathcal{B}(h \to A^0A^0 \to 4 g)$ near 100% is very hard to observe due to huge backgrounds.

Total width $\Gamma_h$ of the Higgs-like particle may be $\gg$ the sum over the partial widths of the SM decays.

$\mathcal{B}(A^0 \to \gamma\gamma) \lesssim 1\%$, but $h \to A^0A^0 \to \gamma\gamma jj$ may still be eventually observed at the LHC. \cite{Chang,Fox,Weiner,hep-ph/0608310,A.Martin,hep-ph/0703247...}
Vectorlike quarks

All Standard Model fermions are chiral: their masses arise from the Higgs coupling.

Vectorlike (i.e. non-chiral) elementary fermions — a new (hypothetical) form of matter.

Masses allowed by $SU(2)_W \times U(1)_Y$ gauge symmetry $\Rightarrow$ naturally heavier than the $t$ quark.

A vectorlike quark $\chi$ which mixes with the top quark:

(B. Dobrescu, KC Kong, R. Mahbubani, 2009)

Higgs boson may lead to the discovery of the vectorlike quark.
Is the Higgs boson an elementary particle or a bound state?

Composite Higgs field as a bound state of the top quark and a vectorlike quark (S. Chivukula, B. Dobrescu, H. Georgi, C. Hill, 1998)

Binding due to some new strongly coupled interaction:
Higgs boson is sensitive to various phenomena beyond the SM.

A lower limit on the Higgs width follows from the LHC and Tevatron rates required for observation.

An upper limit on $\Gamma_h$ follows from the well-motivated assumption that the Higgs coupling to a $W$ or $Z$ pair is not much larger than in the Standard Model.

This range for $\Gamma_h$ allows the extraction of a “span” (i.e., lower and upper limits) for each Higgs coupling.

$\Gamma_h < \Gamma_{\text{max}} \Rightarrow$ an upper limit on the branching fraction of exotic Higgs decays (46% at the 95% CL, if the electroweak symmetry is broken only by doublets).