Prospects for Higgs coupling extraction from LHC

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Outline

- Introduction: what we learn from Higgs couplings

- Coupling extraction strategy*

- Results of past sensitivity studies

- Future strategies

- Conclusions

*I will not talk here about measuring spin, CP, etc.
Higgs couplings in the Standard Model

SM Higgs couplings to SM particles are fixed by the mass-generation mechanism.

$W$ and $Z$:

\[ g_Z \equiv \sqrt{g^2 + g'^2}, \quad v = 246 \text{ GeV} \]

\[ L = \left| D_\mu H \right|^2 \rightarrow \left( \frac{g^2}{4} \right) (h + v)^2 W^+ W^- + \left( \frac{g_Z^2}{8} \right) (h + v)^2 ZZ \]

\[ M^2_W = \frac{g^2 v^2}{4} \quad hWW : i(g^2 v/2) g^{\mu\nu} \]

\[ M^2_Z = \frac{g_Z^2 v^2}{4} \quad hZZ : i(g_Z^2 v/2) g^{\mu\nu} \]

Fermions:

\[ L = -y_f \bar{f}_R H^\dagger Q_L + \cdots \rightarrow -\left( \frac{y_f}{\sqrt{2}} \right) (h + v) \bar{f}_R f_L + \text{h.c.} \]

\[ m_f = \frac{y_f v}{\sqrt{2}} \quad hff : \text{im} f/v \]

Gluon pairs and photon pairs:

induced at 1-loop by fermions, $W$-boson.
Higgs couplings beyond the Standard Model

$W$ and $Z$:

- EWSB can come from more than one Higgs doublet, which then mix to give $h$ mass eigenstate.  \[ v \equiv \sqrt{v_1^2 + v_2^2}, \phi_v = \frac{v_1}{v} h_1 + \frac{v_2}{v} h_2 \]

\[ \mathcal{L} = |D_\mu H_1|^2 + |D_\mu H_2|^2 \]
\[ M_W^2 = \frac{g^2 v^2}{4} \quad hWW : i\langle h|\phi_v\rangle (g^2 v/2) g^{\mu\nu} \equiv i\bar{g}_W (g^2 v/2) g^{\mu\nu} \]
\[ M_Z^2 = \frac{g_Z^2 v^2}{4} \quad hZZ : i\langle h|\phi_v\rangle (g_Z^2 v/2) g^{\mu\nu} \equiv i\bar{g}_Z (g^2 v/2) g^{\mu\nu} \]

Note $\bar{g}_W = \bar{g}_Z$. Also, $\bar{g}_{W,Z} = 1$ when $h = \phi_v$: “decoupling limit”.

- Part of EWSB from larger representation of $SU(2)$.  \[ Q = T^3 + Y/2 \]

\[ \mathcal{L} \supset |D_\mu \Phi|^2 \rightarrow \frac{g^2}{4}[2T(T + 1) - Y^2/2](\phi + v)^2 W^+ W^- + \frac{g_Z^2}{8} Y^2 (\phi + v)^2 ZZ \]

Can get $\bar{g}_W \neq \bar{g}_Z$ and/or $\bar{g}_{W,Z} > 1$ after mixing to form $h$.

Tightly constrained by $\rho$ parameter, $\rho \equiv M_W^2/M_Z^2 \cos^2 \theta_W = 1$ in SM.

*Heather Logan (Carleton U.) Higgs coupling extraction from LHC PI Higgs WS 2012*
Higgs couplings beyond the Standard Model

Fermions:

Masses of different fermions can come from different Higgs doublets, which then mix to give $h$ mass eigenstate:

\[
\mathcal{L} = -y_f \bar{f}_R \Phi_f^\dagger F_L + \text{(other fermions)} + \text{h.c.}
\]

\[
m_f = y_f v_f / \sqrt{2} \quad h \bar{f} f : i \langle h | \phi_f \rangle (v / v_f) m_f / v \equiv i g_f m_f / v
\]

In general $\bar{g}_t \neq \bar{g}_b \neq \bar{g}_\tau$; e.g. MSSM with large $\tan \beta$ ($\Delta_b$).

Note $\langle h | \phi_f \rangle (v / v_f) = \langle h | \phi_f \rangle / \langle \phi_v | \phi_f \rangle$

$\Rightarrow \quad \bar{g}_f = 1$ when $h = \phi_v$: “decoupling limit”.
Higgs couplings beyond the Standard Model

Gluon pairs and photon pairs:

- $\bar{g}_t$ and $\bar{g}_W$ change the normalization of top quark and $W$ loops.

- New coloured or charged particles give new loop contributions.
  e.g. top squark, charginos, charged Higgs in MSSM

New particles in the loop can affect $h \leftrightarrow gg$ and $h \rightarrow \gamma\gamma$ even if $h$ is otherwise SM-like.

$\Rightarrow$ Treat $\bar{g}_g$ and $\bar{g}_\gamma$ as additional independent coupling parameters.
Loop-induced effective couplings: momentum-dependence issues at NLO!
(more on this later)
Coupling extraction strategy

Measure event rates at LHC: sensitive to production and decay couplings. Narrow width approximation:

\[ \text{Rate}_{ij} = \sigma_i \text{BR}_j = \sigma_i \frac{\Gamma_j}{\Gamma_{\text{tot}}} \]

Coupling dependence (at leading order):

\[ \sigma_i = \overline{g}_i^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors}) \]
\[ \Gamma_j = \overline{g}_j^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors}) \]
\[ \Gamma_{\text{tot}} = \sum \Gamma_k = \sum \overline{g}_k^2 \Gamma_k^{\text{SM}} \]

Each rate depends on multiple couplings. \(\rightarrow\) correlations
Coupling extraction strategy

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\[ \Gamma_{\text{tot}} = \sum_k \Gamma_k = \sum_{\text{SM}} \bar{g}_k^2 \Gamma_k^{\text{SM}} + \sum_{\text{new}} \Gamma_k^{\text{new}} \]

Each rate depends on multiple couplings. → correlations

Non-SM decays could also be present:
- invisible final state (can look for this with dedicated searches)
- “unobserved” final state (e.g., \(h \rightarrow \text{jets}\) )
Unobserved final states cause a “flat direction” in the fit.

Allow an unobserved decay mode while simultaneously increasing all couplings to SM particles by a factor $a$:

$$\text{Rate}_{ij} = a^2 \sigma^\text{SM}_i \frac{a^2 \Gamma^\text{SM}_j}{a^2 \Gamma^\text{SM}_{\text{tot}} + \Gamma_{\text{new}}}$$

Ways to deal with this:
- assume no unobserved decays  
  (ok for checking consistency with SM, but highly model-dependent)
- assume $hWW$ and $hZZ$ couplings are no larger than in SM  
  (valid if only SU(2)-doublets/singlets are present)
- include direct measurement of Higgs width  
  (only works for heavier Higgs so that $\Gamma_{\text{tot}} > \text{expt. resolution}$; $\Gamma^\text{SM}_{\text{tot}} \approx 4 \text{ MeV for 125 GeV Higgs}$)

No known model-independent way around this at LHC.  
[Can we measure $h \rightarrow \text{jets}$? Boosted object techniques?]

(ILC gets around this using decay-mode-independent measurement of $e^+e^- \rightarrow Zh$ cross section from recoil-mass method.)

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How to think about the fit

First consider VBF → h → WW:
- Rate = σ(VBF → h) × BR(h → WW).
- use the fact that BR(h → WW) ≤ 1.
  (can include other measured decays in VBF channels to tighten this)
- VBF → h → WW rate then puts a lower bound on σ(VBF → h).
- This puts a lower bound on the hWW, hZZ couplings.
- Calculate lower bound on Γ(h → WW, ZZ) → get a lower bound
  on Γ_{tot}.

Theory assumption that \( \bar{g}_W \leq 1 \) and \( \bar{g}_Z \leq 1 \):
  (i.e., assume hWW and hZZ couplings are no larger than in SM)
- Imposes a theoretical upper bound on σ(VBF → h).
- VBF → h → WW rate puts a lower bound on BR(h → WW).
- Calculate theoretical upper bound on Γ(h → WW) → get an
  upper bound on Γ_{tot}.

\[ Γ_{tot} = Γ(h → WW)/BR(h → WW) \]
How to think about the fit

Now include the other measurements.

\[
\frac{\text{Rate}(A \rightarrow X)}{\text{Rate}(A \rightarrow Y)} = \frac{\sigma(A \rightarrow h) \Gamma(h \rightarrow X)/\Gamma_{\text{tot}}}{\sigma(A \rightarrow h) \Gamma(h \rightarrow Y)/\Gamma_{\text{tot}}} \Rightarrow \frac{g_X^2}{g_Y^2}
\]

\[
\frac{\text{Rate}(A \rightarrow X)}{\text{Rate}(B \rightarrow X)} = \frac{\sigma(A \rightarrow h) \Gamma(h \rightarrow X)/\Gamma_{\text{tot}}}{\sigma(B \rightarrow h) \Gamma(h \rightarrow X)/\Gamma_{\text{tot}}} \Rightarrow \frac{g_A^2}{g_B^2}
\]

Fitted couplings correlated with $\bar{g}_W$ and with each other.

Feed back other fitted couplings into $\Gamma_{\text{tot}}$ calculation; tighten up $\bar{g}_W$ constraint.

(In practice this would be done by an overall log-likelihood fit or similar, rather than iteratively.)
Past studies

Get ratios of Higgs couplings-squared from taking ratios of rates. Full coupling extraction: assume no unexpected decay channels, assume $\bar{g}_b = \bar{g}_\tau$. $M_h = 100–190$ GeV


Add $t\bar{t}h$, $h \rightarrow \tau\tau$ channel to improve $t\bar{t}h$ constraint. $M_h = 110–180$ GeV Belyaev & Reina, JHEP0208, 041 (2002)

Fit assuming $hWW$, $hZZ$ couplings are bounded from above by SM value. $M_h = 110–190$ GeV Dührssen, Heinemeyer, HEL, Rainwater, Weiglein, & Zeppenfeld, PRD70, 113009 (2004)


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Higgs channels used (2004 study, 120–130 GeV):


GF \( gg \rightarrow H \rightarrow WW \)

VBF \( qqH \rightarrow qqWW \)

\( t\bar{t}H, \ H \rightarrow WW \)

GF \( gg \rightarrow H \rightarrow ZZ \)

VBF \( qqH \rightarrow qqZZ \)

VBF \( qqH \rightarrow qq\tau\tau \)

Inclusive \( H \rightarrow \gamma\gamma \)

VBF \( qqH \rightarrow qq\gamma\gamma \)

\( t\bar{t}H, \ H \rightarrow \gamma\gamma \ (M_h \leq 120 \text{ GeV}) \)

\( WH, \ H \rightarrow \gamma\gamma \ (M_h \leq 120 \text{ GeV}) \)

\( ZH, \ H \rightarrow \gamma\gamma \ (M_h \leq 120 \text{ GeV}) \)

\( t\bar{t}H, \ H \rightarrow b\bar{b} \quad \Leftarrow!! \)

All expt numbers from 14 TeV “first 30 fb\(^{-1}\)” studies.
Higgs channels used (2009 study, 120 GeV):

GF \( gg \rightarrow H \rightarrow WW \)
VBF \( qqH \rightarrow qqWW \)
\( t\bar{t}H, \ H \rightarrow WW \)

GF \( gg \rightarrow H \rightarrow ZZ \)
VBF \( qqH \rightarrow qqZZ \)

VBF \( qqH \rightarrow qq\tau\tau \)

Inclusive \( H \rightarrow \gamma\gamma \)
VBF \( qqH \rightarrow qq\gamma\gamma \)
\( t\bar{t}H, \ H \rightarrow \gamma\gamma \ (M_h \leq 120 \text{ GeV}) \)
\( WH, \ H \rightarrow \gamma\gamma \ (M_h \leq 120 \text{ GeV}) \)
\( ZH, \ H \rightarrow \gamma\gamma \ (M_h \leq 120 \text{ GeV}) \)

\( t\bar{t}H, \ H \rightarrow b\bar{b} \times 50\% \) vs. 2004 study
\( WH/ZH, \ H \rightarrow b\bar{b} \) a la Butterworth

All expt numbers from 14 TeV “first 30 fb\(^{-1}\)” studies.
$\Delta \bar{g}_{W,Z}^2 \sim 35\% \rightarrow 25\%$
$\Delta \bar{g}_b^2 \sim 65\% \rightarrow 45\%$
$\Delta \bar{g}_t^2 \sim 60\% \rightarrow 35\%$
$\Delta \bar{g}_T^2 \sim 40\% \rightarrow 25\%$ for 125 GeV Higgs

$\bar{g}_W = \bar{g}_Z \leq 1$

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$\Gamma_{\text{unobs}} \leq 50\% \rightarrow 35\%$ of $\Gamma_{\text{tot,fit}}$

$\Gamma_{\gamma,\text{new}} \in [-25\%, +40\%] \rightarrow [-15\%, +25\%]$ of $\Gamma_{\gamma}$ from $W, t$ loops

$\Gamma_{g,\text{new}} \in [-45\%, +75\%] \rightarrow [-35\%, +40\%]$ of $\Gamma_{g}$ from $t$ loop

for 125 GeV Higgs

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- Much more sophisticated statistical analysis (SFitter)
- Assume no “unexpected” decays

120 GeV Higgs

\[ g_i = g_{i}^{SM}(1 + \Delta_i) \]: alternate minima corresponding to sign flips.

(here: assume no BSM particles in \( hgg, h\gamma\gamma \) loops)
30 fb$^{-1}$, extracted error:  (caution: non-Gaussian)
\[ \Delta_W : \pm 24\% \quad \Delta_Z : \pm 31\% \]
\[ \Delta_t : \pm 53\% \quad \Delta_b : \pm 44\% \quad \Delta_\tau : \pm 31\% \]
\[ \Delta_g : \pm 61\% \quad \Delta_\gamma : \pm 31\% \]

compare 35-65\% on $\Delta g^2$

(SM-decays-only constraint less restrictive than $\bar{g}_{W,Z} \leq 1$)

30 fb$^{-1}$, extracted error on ratios:
\[ \Delta_Z/\Delta_W : \pm 41\% \]
\[ \Delta_t/\Delta_W : \pm 51\% \quad \Delta_b/\Delta_W : 31\% \quad \Delta_\tau/\Delta_W : 28\% \]
\[ \Delta_g/\Delta_W : \pm 61\% \quad \Delta_\gamma/\Delta_W : 30\% \]

Slight improvement due to correlations.
Future strategies 1: experimental questions

How well can we extrapolate measurements to high luminosity?
- Many channels are statistically limited at 30 fb$^{-1}$:
  Pileup is already higher than old “first 30 fb$^{-1}$” studies.
- What happens to VBF channels? minijet veto?
- What happens to $\gamma\gamma$ channels? primary vertex identification?

$h \rightarrow b\bar{b}$ channel(s) are critical.
- Largest Higgs BR at $\sim 125$ GeV: crucial for constraining $\Gamma_{\text{tot}}$.
- Boosted-object $Wh/Zh$, $h \rightarrow b\bar{b}$ [Butterworth et al] is very important in Lafaye et al (2009) fit.
Future strategies 2: fit parameters

Where should theory meet experiment?

- Experimentally-inspired parameterization: Disentangle production and decay in a uniform way?
\[
\sigma(A \rightarrow h) \cdot \text{BR}(H \rightarrow X) \propto \Gamma_A \Gamma_X / \Gamma_{\text{tot}}
\]
\[
\Gamma_W / \sqrt{\Gamma_{\text{tot}}}; \quad \Gamma_Z / \sqrt{\Gamma_{\text{tot}}}
\]
\[
\Gamma_t / \sqrt{\Gamma_{\text{tot}}}; \quad \Gamma_b / \sqrt{\Gamma_{\text{tot}}}; \quad \Gamma_\tau / \sqrt{\Gamma_{\text{tot}}}
\]
\[
\Gamma_g / \sqrt{\Gamma_{\text{tot}}}; \quad \Gamma_\gamma / \sqrt{\Gamma_{\text{tot}}}
\]

- Theoretically-inspired parameterization:
\[
\bar{g}_W, \bar{g}_Z, \bar{g}_t, \bar{g}_b, \bar{g}_\tau: \text{ need unambiguous definitions at NLO}
\]
\[
\Gamma_{g,\text{new}}, \Gamma_{\gamma,\text{new}}: \text{BSM particles in } gg, \gamma\gamma \text{ loops}
\]
\[
\Gamma_{\text{invis}} (\text{use dedicated } h \rightarrow \text{invisible channels})
\]
\[
\Gamma_{\text{unobs}} (\text{includes } c\bar{c}, gg, \text{light } q \text{ jets, etc.})
\]

- Always need to input a theory assumption because of \(\Gamma_{\text{unobs}}\).

[Can we measure \(h \rightarrow \text{jets? Boosted object techniques?]}

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Future strategies 3: coupling dependence at NLO

Coupling dependence of production and decay is not “pure”, even at the theory level.

- Interference between $4f$ final states from $WW$ and $ZZ$ decays non-negligible below $WW$ threshold.

- EW RCs to $h \to WW$ introduce dependence on $y_t$.

- Nonstandard production modes like $b\bar{b} \to h$.

- $\sigma(A \to h) \cdot \text{BR}(H \to X) \propto \Gamma_A \Gamma_X / \Gamma_{tot}$ is not strictly true at NLO: different kinematics in production and decay can shift relative contributions of underlying couplings.
Future strategies 4: Higgs mass as an input

SM Higgs couplings to all SM particles are fixed by the mass-generation mechanism → variation with $M_h$ is due to kinematics.

![Graph showing Higgs branching ratios and total uncertainty as a function of Higgs mass](image)

1 GeV uncertainty in $M_h \Rightarrow 5\%$ uncertainty in $g_b/g_W$.
100 MeV uncertainty in $M_h \Rightarrow 0.5\%$ uncertainty in $g_b/g_W$.
$M_h$ could be included as a correlated fit parameter.

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Conclusions

LHC data will let us measure Higgs couplings to $W, Z, t, b, \tau, gg, \gamma\gamma$.

Close interaction between theorists and experimentalists is essential for best outcome.
- Light Mass Higgs subgroup of LHC Higgs Cross Section Working Group (see the CERN twiki)

Are there Higgs-coupling-related considerations that will influence LHC run plan?
(impact of pileup, detector upgrades, ...)

Important to make projections of LHC's ultimate Higgs coupling precision for planning for future colliders (ILC, CLIC?).
By how much would ILC measurements improve our knowledge?

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The Carleton Theory Group wants YOU!

Openings for up to 4 M.Sc. or Ph.D. students starting September 2012

Work on LHC phenomenology and model building with Profs. Steve Godfrey or Thomas Grégoire
To test SM Higgs mechanism, need to measure Higgs couplings.

**SM:** coupling of Higgs to each SM particle already fixed by known particle masses.

**BSM:** pattern of deviations from SM expectations characterizes BSM model.

*ACFA report*