The Higgs boson: where we go from here

Heather Logan

Carleton University

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Outline

Introduction: a long-expected particle

Higgs discovery and current status

Higgs measurements: what we hope to learn

Experimental prospects

Conclusions
INTRODUCTION

Electroweak interactions are described by a spontaneously broken gauge theory.

Gauge theory: extremely predictive, need only two input parameters: couplings $g$ and $g'$ of SU(2) and U(1) parts.

Spontaneously broken: preserve the predictivity of the gauge theory while giving masses to $W$ and $Z$ bosons and fermions. Need third input parameter: vacuum condensate $v$.

Measure $(g,g',v)$ or equivalently $(M_Z, \alpha_{EM}, G_F)$; predict all other observables. Works very well.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>$\Delta O_{meas} - O_{fit}$/$\sigma_{meas}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha_{\text{had}}^{(0)}(m_Z)$</td>
<td>0.02750 $\pm$ 0.00033</td>
<td>0.02759</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 $\pm$ 0.0021</td>
<td>91.1874</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 $\pm$ 0.0023</td>
<td>2.4959</td>
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<tr>
<td>$\alpha_{\text{had}}^{[\text{nb}]}$</td>
<td>41.540 $\pm$ 0.037</td>
<td>41.478</td>
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<tr>
<td>$R_l$</td>
<td>20.767 $\pm$ 0.025</td>
<td>20.742</td>
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<tr>
<td>$A_{\text{fb}}^{0,1}$</td>
<td>0.01714 $\pm$ 0.00095</td>
<td>0.01645</td>
</tr>
<tr>
<td>$A_{\text{(P)}l}$</td>
<td>0.1465 $\pm$ 0.0032</td>
<td>0.1481</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 $\pm$ 0.00066</td>
<td>0.21579</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1721 $\pm$ 0.0030</td>
<td>0.1723</td>
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<tr>
<td>$A_{\text{b,b}}$</td>
<td>0.0992 $\pm$ 0.0016</td>
<td>0.1038</td>
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<tr>
<td>$A_{\text{b,c}}$</td>
<td>0.0707 $\pm$ 0.0035</td>
<td>0.0742</td>
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<td>$A_{\text{b}}$</td>
<td>0.923 $\pm$ 0.020</td>
<td>0.935</td>
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<tr>
<td>$A_{\text{c}}$</td>
<td>0.670 $\pm$ 0.027</td>
<td>0.668</td>
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<tr>
<td>$A_l^{(\text{SLD})}$</td>
<td>0.1513 $\pm$ 0.0021</td>
<td>0.1481</td>
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<tr>
<td>$\sin^2 \theta_{\text{eff}}^{(\text{Q}_{\text{b}})}$</td>
<td>0.2324 $\pm$ 0.0012</td>
<td>0.2314</td>
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<tr>
<td>$m_W$ [GeV]</td>
<td>80.385 $\pm$ 0.015</td>
<td>80.377</td>
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<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.085 $\pm$ 0.042</td>
<td>2.092</td>
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<tr>
<td>$m_t$ [GeV]</td>
<td>173.20 $\pm$ 0.90</td>
<td>173.26</td>
</tr>
</tbody>
</table>

March 2012

LEP Electroweak WG, Winter 2012

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Higgs boson
UdeM/McGill Feb 2013
Spontaneously broken electroweak theory can be described by a Chiral Lagrangian (with no reference to a Higgs).

The pure electroweak theory looks like this:

\[ \mathcal{L} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^a{\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G^a{\mu\nu} + \bar{\psi}_i D_\mu \gamma^\mu \psi_i \]

- Describes gauge and fermion fields and their interactions.
- Everything must be massless!

In order to put in masses consistent with gauge invariance, fermions and gauge bosons need to couple to a weak-charged vacuum condensate:

\[ \langle \Sigma \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \]

Here \( v \equiv 246 \) GeV is a constant.

We know its value from muon decay, \( G_F = 1/\sqrt{2}v^2 \).

\( v \equiv \) vacuum expectation value; the \( \sqrt{2} \) is a conventional normalization

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Put in a gauge-kinetic term for \( \Sigma \) and interactions with fermions:

\[
\mathcal{L} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \bar{\psi}_i D_\mu \gamma^\mu \psi_i \\
+ (D_\mu \Sigma)^\dagger (D^\mu \Sigma) - y_{ij} \bar{\psi}_i \Sigma \psi_j
\]

- These generate the \( W, Z, \) and fermion masses \( \propto v. \)

Let's see what happens when we do gauge transformations:

Recall in electromagnetism: \( A^\mu \to A^\mu - \partial^\mu \lambda(x), \psi \to e^{-i\lambda(x)}\psi. \)

\[
\begin{pmatrix}
0 \\
v/\sqrt{2}
\end{pmatrix} \to \Sigma \equiv e^{-i\xi^a(x)\sigma^a/v} \begin{pmatrix}
0 \\
v/\sqrt{2}
\end{pmatrix} = \begin{pmatrix}
\left[ -\xi^2(x) - i\xi^1(x) \right]/\sqrt{2} \\
v + i\xi^3(x)/\sqrt{2}
\end{pmatrix} + \cdots
\]

\( \sigma^a \) are the three Pauli spin matrices.

- The \( \xi^a \) degrees of freedom correspond to the third polarization states of the massive \( W \) and \( Z. \)

This “nonlinear sigma model” is nonrenormalizable and breaks down at a scale around \( 4\pi \langle \Sigma \rangle \sim 1.5 \) TeV. Breakdown is revealed by nonsensical results for high-energy scattering processes.
Scattering of longitudinally-polarized $W$s

\[ \text{SU}(2) \times \text{U}(1) @ E^4 \]

Graphs

\[
\begin{align*}
\text{(a)} & \quad -3 + 6 \cos \theta + \cos^2 \theta \\
\text{(b)} & \quad -4 \cos \theta \\
\text{(c)} & \quad +3 - 2 \cos \theta - \cos^2 \theta
\end{align*}
\]

Sum \[ 0 \]

\[ \epsilon^\mu_L(k) = \frac{k^\mu}{m_w} + O\left(\frac{m_w}{E}\right) \]

Graphics from R.S. Chivukula, LHC4ILC 2007
Scattering of longitudinally-polarized $W$s exposes need for a Higgs

\[ \text{SU}(2) \times \text{U}(1) @ E^2 \]

\[ \frac{g^2 E^2}{m_w^2} \]

\begin{align*}
(a) & \quad +2 - 6 \cos \theta \\
(b) & \quad - \cos \theta \\
(c) & \quad -\frac{3}{2} + \frac{15}{2} \cos \theta \\
(d + e) & \quad -\frac{1}{2} - \frac{1}{2} \cos \theta
\end{align*}

\[ \sum \quad 0 \]

\[ \theta(E^0) \Rightarrow 4d \ m_H \ \text{bound:} \ m_H < \sqrt{\frac{16\pi}{3} v} \simeq 1.0 \ \text{TeV} \]

\[ \text{If no Higgs} \Rightarrow \theta(E^2) \Rightarrow E < \sqrt{8\pi v} \simeq 1.2 \ \text{TeV} \]

*or something to play its role
$\Sigma$ is formally dimensionless (in terms of fields).

Can add powers of an extra scalar field $h$ up to dimension 4:

$$\mathcal{L} = \frac{-1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \bar{\psi}_i \mathcal{D}_\mu \gamma^\mu \psi_i$$

$$+ (\mathcal{D}_\mu \Sigma)^\dagger (\mathcal{D}^\mu \Sigma) \left(1 + a \frac{2h}{v} + b \frac{h^2}{v^2}\right) - y_{ij} \bar{\psi}_i \Sigma \psi_j \left(1 + c \frac{h}{v}\right)$$

Unitarity of tree-level scattering amplitudes:

$V_L V_L \rightarrow V_L V_L$ is unitarized by $h$ if $a = 1$

$V_L V_L \rightarrow f \bar{f}$ is unitarized by $h$ if $c = 1$

$V_L V_L \rightarrow h h$ is unitarized if $b = a^2$

With $a = b = c = 1$, can absorb $h$ into the $\Sigma$ field to make a “linear sigma model”, i.e., the Standard Model Higgs field:

$$\overline{\Sigma} = e^{-i \xi^a (x) \sigma^a / v} \begin{pmatrix} 0 \\ (v + h) / \sqrt{2} \end{pmatrix}$$
Higgs couplings in the Standard Model:

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

$W$ and $Z$: 
\[ g_Z \equiv \sqrt{g^2 + g'^2}, \quad v = 246 \text{ GeV} \]
\[ L = |D_\mu H|^2 \rightarrow (g^2/4)(h + v)^2W^+W^- + (g^2_Z/8)(h + v)^2ZZ \]
\[ M_W^2 = g^2v^2/4 \quad hWW : \quad i(g^2v/2)g^{\mu\nu} \]
\[ M_Z^2 = g^2_Zv^2/4 \quad hZZ : \quad i(g^2_Zv/2)g^{\mu\nu} \]

Fermions:
\[ L = -y_f \bar{f}_R H^\dagger Q_L + \cdots \rightarrow -(y_f/\sqrt{2})(h + v)\bar{f}_R f_L + h.c. \]
\[ m_f = y_f v/\sqrt{2} \quad hff : \quad im_f/v \]

Gluon pairs and photon pairs:  
induced at 1-loop by fermions, $W$-boson.

The only undetermined parameter is the Higgs mass.
Predict SM Higgs production cross sections (as function of $M_h$)

$\sqrt{s} = 8$ TeV

$\sigma(pp \rightarrow H+X) \text{ [pb]}$

$H (NNLO+NNLL \text{ QCD} + \text{NLO EW})$

$pp \rightarrow qqH (\text{NNLO QCD}+\text{NLO EW})$

$pp \rightarrow WH (\text{NNLO QCD}+\text{NLO EW})$

$pp \rightarrow ZH (\text{NNLO QCD}+\text{NLO EW})$

$pp \rightarrow ttH (\text{NLO QCD})$

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Predict SM Higgs decay branching ratios (as function of $M_h$)
What is the Higgs mass?

Upper bound on Higgs mass from $VV \rightarrow VV$: Lee, Quigg, Thacker 1977

$$M_h^2 \leq \frac{8\pi v^2}{3} \simeq (710 \text{ GeV})^2$$

Coupled channel analysis, $|\text{Re} a_0| \leq 1/2$, $v \simeq 246$ GeV.

Electroweak fit in the SM:

Sensitive to $M_h$ through 1-loop corrections to $W$ and $Z$ propagators.

Logarithmic dependence on $M_h$:

$M_h \lesssim 160$–$200$ GeV

(known since late ’90s)

Constraint valid only in SM: fit to one remaining free parameter.

LEP Electroweak Working Group, Winter 2012

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HIGGS DISCOVERY AND CURRENT STATUS

A new particle consistent with being the SM Higgs boson was discovered last summer at the LHC.

\[ h \rightarrow \gamma\gamma \quad \text{and} \quad h \rightarrow ZZ^* \rightarrow 4\ell \]

ATLAS discovery plots, July 4, 2012

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HIGGS DISCOVERY AND CURRENT STATUS

A new particle consistent with being the SM Higgs boson was discovered last summer at the LHC.

\[ h \rightarrow \gamma\gamma \]

\[ h \rightarrow ZZ^* \rightarrow 4\ell \]

CMS discovery plots, July 4, 2012

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More data collected and analyzed since then.

**December 2012:** 17–18 fb$^{-1}$ analyzed per expt (7 and 8 TeV)

![Graph](image1)

**January 2013:** 27 fb$^{-1}$ collected per expt (7 and 8 TeV)

Expect new analysis results for Moriond conferences (March)

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No evidence for additional Higgs-like states.
Within the SM, the only parameter left to be measured is $M_h$.

The interest in measuring Higgs couplings is to see if there is non-SM Higgs physics!
We know that the Standard Model cannot be the whole story.

Problems from data:

- Dark matter (and dark energy?!?)

- Matter-antimatter asymmetry

Problems from theory:

- Hierarchy problem

- Neutrino masses (why so very tiny?)

- Flavour (origin of quark and lepton masses, mixing, CP violation?)
We know that the Standard Model cannot be the whole story.

Problems from data:

- Dark matter (and dark energy?!?)
  
  Higgs portal; $h \rightarrow$ invisible
- Matter-antimatter asymmetry
  
  Electroweak baryogenesis, need modified Higgs potential

Problems from theory:

- Hierarchy problem
  
  SUSY; composite Higgs/Randall-Sundrum; little Higgs
- Neutrino masses (why so very tiny?)
  
  Type-2 seesaw scalar triplet; neutrino-coupled doublet
- Flavour (origin of quark and lepton masses, mixing, CP violation?)
  
  Clues from fermion couplings to Higgs?
To probe for this new physics:

**Measure couplings of the discovered Higgs particle** \( h \)

- Mixing within extended Higgs sector shows up in \( h \) couplings

- New charged/coloured particles contribute to \( h\gamma\gamma, hgg \) loops

- Compositeness effects at order \( v^2/f^2 \)

**Search directly for the new states**

- Adapt SM Higgs searches; \( h \) coupling measurements constrain production/decay of additional states

- \( h \rightarrow \) new particles
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.
  \[ v \equiv \sqrt{v_1^2 + v_2^2}, \phi_v = \frac{v_1}{v}h_1 + \frac{v_2}{v}h_2 \]
  \[ \mathcal{L} = |D_\mu H_1|^2 + |D_\mu H_2|^2 \]
  \[ M_W^2 = g^2v^2/4 \quad hWW : \quad i\langle h|\phi_v\rangle(g^2v/2)g^{\mu\nu} \equiv i\bar{g}_W(g^2v/2)g^{\mu\nu} \]
  \[ M_Z^2 = g_Z^2v^2/4 \quad hZZ : \quad i\langle h|\phi_v\rangle(g_Z^2v/2)g^{\mu\nu} \equiv i\bar{g}_Z(g^2v/2)g^{\mu\nu} \]

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).
  \[ Q = T^3 + Y/2 \]
  \[ \mathcal{L} \supset |D_\mu \Phi|^2 \rightarrow (g^2/4)[2T(T + 1) - Y^2/2](\phi + v)^2W^+W^- + (g_Z^2/8)Y^2(\phi + v)^2ZZ \]

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.
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:

$$\mathcal{L} = -y_f \bar{f}_R \Phi^\dagger_f F_L + \text{(other fermions)} + \text{h.c.}$$

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

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

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

$\Rightarrow \bar{g}_f = 1$ 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.

⇒ Treat $\bar{g}_g$ and $\bar{g}_\gamma$ as additional independent coupling parameters.

Loop-induced effective couplings: momentum-dependence issues at NLO!
Higgs couplings **beyond** the Standard Model

**Composite Higgs:**

- Strongly-interacting sector contributes to gauge boson & fermion masses along with $h$

- Deviations in couplings $\bar{g}_V, \bar{g}_f \neq 1$ can be parameterized in terms of higher-dimensional operators: $\sim 1 + \mathcal{O}(v^2/f^2)$

  \[ f = \text{scale of strong interactions; typically } f \gg v. \]

**Examples:**

- Little Higgs models
  (also often contain additional Higgs doublets, triplets)

- 5-dimensional Composite Higgs models
LHC measurements to date (Dec 2012)

Overall signal strength $\mu \equiv \sigma/\sigma_{SM}$
- Assume that all decays are in their SM proportions

1-parameter coupling measurement

(CMS: 68% CL contours)
This can be interpreted in concrete non-SM Higgs models

SM Higgs mixed with a gauge-singlet scalar:

- Overall 1-parameter scaling of all couplings by \( 0 \leq \cos \theta \leq 1 \).
- BRs stay unchanged; rates scaled by \( \cos^2 \theta \equiv \mu = \sigma/\sigma_{SM} \)

→ Expect to find the orthogonal state somewhere!

SM Higgs with unobserved/invisible decays (e.g. to dark matter):

- Production rates unchanged
- BRs scaled by \( \Gamma_{SM}/(\Gamma_{SM} + \Gamma_{new}) \equiv \mu = \sigma/\sigma_{SM} \)

unless new decay mode is picked up by SM signal/background selections and modifies kinematic shapes.

→ Expect to observe invisible decay channel in a missing-energy search!
Going beyond one parameter: 

\[ \mathcal{L} \supset \frac{v^2}{4} g^2 V_\mu V^\mu \left( a \frac{2h}{v} \right) - m_i \bar{\psi}_i \psi_i \left( c \frac{h}{v} \right) \]

\[ a \equiv \kappa_V \]

(scaling of vector boson couplings)

\[ c \equiv \kappa_F \]

(scaling of fermion couplings)

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This can be interpreted in concrete non-SM Higgs models

Composite Higgs models:

MCHM4: \( a = \sqrt{1 - \xi} \), \( c = (1 - 2\xi)/\sqrt{1 - \xi} \)
MCHM5: \( a = \sqrt{1 - \xi} \), \( c = \sqrt{1 - \xi} \)

Only one underlying parameter: can do a 1-dimensional fit for \( \xi \)!

Type-I 2HDM:

\( a = \sin(\beta - \alpha) \)
\( c = \sin(\beta - \alpha) + \cot \beta \cos(\beta - \alpha) \)

Additional effect in 2HDM-I:
\( H^+ \) gives small contribution to \( h \to \gamma\gamma \) loop (neglected here).

“Fermiophobic” is \( c = 0, a = 1 \) (not a realistic model; excluded)
“Gaugephobic” is \( c = 1, a = 0 \) (excluded)
Going beyond fermion universality: let $g_t \neq g_b$

3 parameters: $\kappa_V = \bar{g}_V$, $\kappa_u = \bar{g}_t$, $\lambda_{du} = \bar{g}_b / \bar{g}_t$.
(Marginalized over the unshown parameter.)

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This can be interpreted in concrete non-SM Higgs models

Type-II 2HDM or MSSM:

\[ \bar{g}_V = \sin(\beta - \alpha) \]
\[ \bar{g}_t = \sin(\beta - \alpha) + \cot \beta \cos(\beta - \alpha) \]
\[ \bar{g}_b = \bar{g}_\tau = \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha) \]

Only 2 underlying free parameters (mixing angles \( \alpha \) and \( \beta \)):
can do a 2-dim fit for \( \alpha \) and \( \beta \)!

Warning: theorist-made fit \( \rightarrow \)

Additional effect in 2HDM-II:

\( H^+ \) gives small contribution to \( h \rightarrow \gamma \gamma \) loop (neglected here).

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Chen and Dawson, 1301.0309
A note on Higgs mass dependence

Variation of SM Higgs BRs with $M_h$ is all due to kinematics.

1 GeV uncertainty in $M_h \Rightarrow 5\%$ uncertainty in $\bar{g}_b/\bar{g}_W$.
100 MeV uncertainty in $M_h \Rightarrow 0.5\%$ uncertainty in $\bar{g}_b/\bar{g}_W$.

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A note on Higgs mass dependence

**ATLAS** Preliminary

**W, Z, H → bb**
- $\sqrt{s} = 7$ TeV: $\int L dt = 4.7$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV: $\int L dt = 13$ fb$^{-1}$

**H → ττ**
- $\sqrt{s} = 7$ TeV: $\int L dt = 4.6$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV: $\int L dt = 13$ fb$^{-1}$

**H → WW$^{(*)}$ → lvlv**
- $\sqrt{s} = 8$ TeV: $\int L dt = 13$ fb$^{-1}$

**H → γγ**
- $\sqrt{s} = 7$ TeV: $\int L dt = 4.8$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV: $\int L dt = 13$ fb$^{-1}$

**H → ZZ$^{(*)}$ → 4l**
- $\sqrt{s} = 7$ TeV: $\int L dt = 4.6$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV: $\int L dt = 13$ fb$^{-1}$

**Combined**
- $\mu = 1.41 \pm 0.26$

$\sqrt{s}$ = 7 TeV: $\int L dt = 4.6 - 4.8$ fb$^{-1}$
$\sqrt{s}$ = 8 TeV: $\int L dt = 13$ fb$^{-1}$

ATLAS Higgs combination December 2012

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A note on Higgs mass dependence

**ATLAS Preliminary**

\[
\begin{align*}
W, Z, H \to bb & \quad \bar{s} = 7 \text{ TeV: } \int L dt = 4.7 \text{ fb}^{-1} \\
& \quad \bar{s} = 8 \text{ TeV: } \int L dt = 13 \text{ fb}^{-1} \\
H \to \tau\tau & \quad \bar{s} = 7 \text{ TeV: } \int L dt = 4.6 \text{ fb}^{-1} \\
& \quad \bar{s} = 8 \text{ TeV: } \int L dt = 13 \text{ fb}^{-1} \\
H \to WW^\ast \to llvv & \quad \bar{s} = 8 \text{ TeV: } \int L dt = 13 \text{ fb}^{-1} \\
H \to \gamma\gamma & \quad \bar{s} = 7 \text{ TeV: } \int L dt = 4.8 \text{ fb}^{-1} \\
& \quad \bar{s} = 8 \text{ TeV: } \int L dt = 13 \text{ fb}^{-1} \\
H \to ZZ^\ast \to 4\ell & \quad \bar{s} = 7 \text{ TeV: } \int L dt = 4.6 \text{ fb}^{-1} \\
& \quad \bar{s} = 8 \text{ TeV: } \int L dt = 13 \text{ fb}^{-1} \\
\text{Combined} & \quad \mu = 1.37 \pm 0.25 \\
& \quad \bar{s} = 7 \text{ TeV: } \int L dt = 4.6 - 4.8 \text{ fb}^{-1} \\
& \quad \bar{s} = 8 \text{ TeV: } \int L dt = 13 \text{ fb}^{-1}
\end{align*}
\]

\[m_h = 124.5 \text{ GeV}\]

**ATLAS Higgs combination December 2012**

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*Higgs boson*

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A note on Higgs mass dependence

ATLAS Preliminary

$W, Z \ H \to bb$
- $\sqrt{s} = 7 \text{ TeV}: \int L dt = 4.7 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1}$

$H \to \tau\tau$
- $\sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1}$

$H \to WW^{(*)} \to ll\nu\nu$
- $\sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1}$

$H \to \gamma\gamma$
- $\sqrt{s} = 7 \text{ TeV}: \int L dt = 4.8 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1}$

$H \to ZZ^{(*)} \to 4l$
- $\sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1}$

Combined
- $\sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6 - 4.8 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1}$

$\mu = 1.33 \pm 0.24$

Signal strength ($\mu$)

$m_H = 125.5 \text{ GeV}$
A note on Higgs mass dependence

**ATLAS** Preliminary

\[ W, Z H \rightarrow bb \]
\[ \sqrt{s} = 7 \text{ TeV}: \int L dt = 4.7 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1} \]

\[ H \rightarrow \tau\tau \]
\[ \sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1} \]

\[ H \rightarrow WW^{(*)} \rightarrow ll\nu\nu \]
\[ \sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1} \]

\[ H \rightarrow \gamma\gamma \]
\[ \sqrt{s} = 7 \text{ TeV}: \int L dt = 4.8 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1} \]

\[ H \rightarrow ZZ^{(*)} \rightarrow 4l \]
\[ \sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1} \]

\[ \text{Combined} \quad \mu = 1.26 \pm 0.23 \]
\[ \sqrt{s} = 7 \text{ TeV}: \int L dt = 4.6 - 4.8 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}: \int L dt = 13 \text{ fb}^{-1} \]

\[ m_H = 126.5 \text{ GeV} \]

---

ATLAS Higgs combination December 2012

Heather Logan (Carleton U.)  
Higgs boson  
UdeM/McGill Feb 2013

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Synergy between couplings of $h$ and searches for additional states

The vacuum condensate(s) generate mass through couplings to SM particles.

If more than one mass eigenstate contains excitation(s) of the condensate(s), then they must share these couplings.

Important implications for searches for additional Higgs-like states.
SM Higgs mixed with a gauge-singlet scalar:

\[ h = \phi \cos \theta - s \sin \theta \quad \quad H = \phi \sin \theta + s \cos \theta \]

Couplings of \( h \): \( \bar{g}_V = \bar{g}_f = \cos \theta \)
Couplings of \( H \): \( \bar{g}_V = \bar{g}_f = \sin \theta \)

- Constrain \( \cos^2 \theta \equiv \sigma/\sigma_{SM} \) of discovered state \( h \).
- Predict production cross section \( \sigma(H) = \sin^2 \theta \sigma_{SM} \).
- BRs of \( H \) are same as SM Higgs (unless \( H \to hh \)).
- Total width of \( H \) is \( \Gamma_H = \sin^2 \theta \Gamma_{SM} \) (unless \( H \to hh \)).

Dedicated searches for \( H \): probe \( \sigma/\sigma_{SM} \) as function of \( M_H, \Gamma_H \).
Two Higgs doublet models:

\[ h = -\sin \alpha \phi_1 + \cos \alpha \phi_2 \quad H = \cos \alpha \phi_1 + \sin \alpha \phi_2 \]

Vector couplings of \( h \): \( \bar{g}_V = \sin(\beta - \alpha) \)
Vector couplings of \( H \): \( \bar{g}_V = \cos(\beta - \alpha) \)

**Type I:**

Fermion couplings of \( h \): \( \bar{g}_f = \sin(\beta - \alpha) + \cot \beta \cos(\beta - \alpha) \)
Fermion couplings of \( H \): \( \bar{g}_f = \cos(\beta - \alpha) - \cot \beta \sin(\beta - \alpha) \)

**Type II or MSSM:**

Fermion couplings of \( h \): \( \bar{g}_t = \sin(\beta - \alpha) + \cot \beta \cos(\beta - \alpha) \)
\[ \bar{g}_b = \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha) \]
Fermion couplings of \( H \): \( \bar{g}_t = \cos(\beta - \alpha) - \cot \beta \sin(\beta - \alpha) \)
\[ \bar{g}_b = \cos(\beta - \alpha) + \tan \beta \sin(\beta - \alpha) \]

Constrain couplings of \( h \) → predict production and decays of \( H \)
Mass of $H$ is constrained by same physics as SM Higgs mass.

$WW \rightarrow WW$ scattering:

If $a \neq 1$, $h$ only partly unitarizes $WW \rightarrow WW$. Job finished by $H$.

$$M_H^2 \lesssim \frac{4\pi v^2}{|1 - a^2|} \approx \frac{(870 \text{ GeV})^2}{|1 - a^2|}$$

Electroweak fit:

SM + singlet:

$$S = a^2 S_{SM}(M_h) + (1 - a^2) S_{SM}(M_H)$$

Similar for $T$ parameter.

Depends on $\log(M_H)$.

2HDM: Similar effects; additional contrib’ns from $H^\pm, A^0$

Can evade limit with new physics.

Gupta, Rzehak, Wells, 1206.3560
Uncertainties on signal strengths are quite large: statistics-limited.
- $bb$, $\tau\tau$ final states only really an upper bound.
- Gauge-initiated processes $Wh$, $Zh$, WBF not yet clearly seen.

Can expect at Moriond: more statistics, improved analyses.
About 27 $\text{fb}^{-1}$ collected per expt. at 7 + 8 TeV up to now.

Expect 300 $\text{fb}^{-1}$/expt. at 13-14 TeV
- Also, larger cross sections

Expected precisions:
\[ \sim 30\% \text{ for } h \rightarrow WW, \text{ VBF } h \rightarrow \gamma\gamma \]
\[ \sim 20\% \text{ for VBF } h \rightarrow \tau\tau \]
\[ \sim 10\% \text{ for } h \rightarrow ZZ, h \rightarrow \gamma\gamma \]

High-luminosity LHC upgrade
> 2022, $\rightarrow$ 3000 $\text{fb}^{-1}$/expt.

Add $tth$ channels $\sim 20\%$, $h \rightarrow \mu\mu$

Improve VBF, $Vh h \rightarrow \gamma\gamma$ 15-30%

More careful studies needed for $h \rightarrow bb$.  

**ATLAS** Preliminary (Simulation)
\[ \sqrt{s} = 14 \text{ TeV} \; \int Ldt=300 \text{ fb}^{-1} ; \int Ldt=3000 \text{ fb}^{-1} \]
\[ \int Ldt=300 \text{ fb}^{-1} \text{ extrapolated from 7+8 TeV} \]

<table>
<thead>
<tr>
<th>Higgs decay channel</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
</tr>
</thead>
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<tr>
<td>$H \rightarrow \mu\mu$</td>
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<tr>
<td>$ttH, H \rightarrow \mu\mu$</td>
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<tr>
<td>$VBF, H \rightarrow \tau\tau$</td>
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<td>$H \rightarrow ZZ$</td>
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<td>$VBF, H \rightarrow WW$</td>
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<td>$H \rightarrow WW$</td>
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<td>$VH, H \rightarrow \gamma\gamma$</td>
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<td>$ttH, H \rightarrow \gamma\gamma$</td>
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<td>$VBF, H \rightarrow \gamma\gamma$</td>
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<td>$H \rightarrow \gamma\gamma (+j)$</td>
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<tr>
<td>$H \rightarrow \gamma\gamma$</td>
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</tr>
</tbody>
</table>
Extracting individual Higgs couplings:
- need to do a fit of multiple channels
- LHC: must make theory assumption to constrain total width

\[ \frac{g(hAA)}{g(hAA)}|_{SM} - 1 \quad \text{LHC} \]

Peskin, 1207.2516. LHC is 300 fb\(^{-1}\), includes Sep 2012 European Strategy submissions.

Can still do fits within specific models: limited parameter set leverages most precise measurements.

Heather Logan (Carleton U.)  Higgs boson  UdeM/McGill Feb 2013
For higher precision: $e^+e^-$ Higgs factory

**ILC: 250 fb$^{-1}$ at 250 GeV:** peak of $e^+e^-$ → $Zh$ cross section
- “Tagged” Higgs: measure $\sigma(Zh)$ independent of BRs to 2.5%
- BRs to $bb$ ($< 3\%$), $\tau\tau$, $cc$ ($\sim 7\%$), $WW$, $gg$ ($\sim 9\%$)
- BRs to $ZZ$, $\gamma\gamma$ statistics limited (20-30%)

**ILC: 500 fb$^{-1}$ at 500 GeV:**
- WBF $e^+e^- \rightarrow \nu\bar{\nu}h$: $\Gamma_{\text{tot}}$ from combining with BR($WW$)
- $e^+e^- \rightarrow tth$ for top quark Yukawa coupling
- $e^+e^- \rightarrow Zhh$ for Higgs self-coupling ($\sim 27\%$ with 2000 fb$^{-1}$)

**ILC upgrade: 1000 fb$^{-1}$ at 1000 GeV:**
- ultimate precision on $\sigma \times$BRs
- $e^+e^- \rightarrow \nu\bar{\nu}hh$ for Higgs self-coupling ($\sim 20\%$ with 2000 fb$^{-1}$)
For higher precision: $e^+e^-$ Higgs factory

\[
g(hAA)/g(hAA)_{SM}-1 \quad \text{LHC/ILC1/ILC/ILCTeV}
\]

Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) $1\sigma$ confidence intervals for LHC at 14 TeV with 300 fb$^{-1}$, for ILC at 250 GeV and 250 fb$^{-1}$ (ILC1), for the full ILC program up to 500 GeV with 500 fb$^{-1}$ (ILC), and for a program with 1000 fb$^{-1}$ for an upgraded ILC at 1 TeV (ILCTeV). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

Peskin, 1207.2516. LHC is 300 fb$^{-1}$, includes Sep 2012 European Strategy submissions.

Heather Logan (Carleton U.) Higgs boson UdeM/McGill Feb 2013
CONCLUSIONS

Higgs discovery begins an era of precision Higgs measurements.

Theory:
- Refine our understanding of non-SM Higgs models
  (what do measurements tell us about the underlying physics?)
- Precise predictions for expt observables in SM, BSM models

Experiment:
- Sharpen analyses for best coupling sensitivity
- LHC upgrades to complete 300 fb$^{-1}$ program
- Prepare for the future: HL-LHC? ILC?
What do we learn by measuring Higgs couplings?

- Is our Higgs fully responsible for generating the masses of $W$, $Z$, and fermions?

- Is our Higgs fully responsible for unitarizing longitudinal gauge boson scattering?

- Is our Higgs the only excitation of the vacuum condensate?

Is there other physics needed to complete any of these? (and if so, what is its energy scale?)

- Is there other stuff out there that couples to our Higgs?
Why fit to specific models?

Specific models correspond to a lower-dimensional “slice” through the most general (e.g., 5+2 dimensional) Higgs coupling parameter space.

- Test overall (in-)consistency with a model’s coupling pattern
- Get much tighter constraints on a few model parameters than on many independent Higgs couplings

Ideal world: do general fit plus all of the above!

Ultimate test of LHC Higgs coupling sensitivity is the “decoupling limit” of small deviations from SM couplings.
This can be interpreted in concrete non-SM Higgs models

**Type-II, lepton-specific, “flipped” 2HDMs:**
Only 2 underlying free parameters (mixing angles $\alpha$ and $\beta$), plus small contribution of $H^+$ to $h \rightarrow \gamma\gamma$ loop

$$hWW, \ hZZ \propto a = \sin(\beta - \alpha)$$

Type-II: $h\bar{t}t \propto c_1 = \cos \alpha / \sin \beta$; $h\bar{b}b$, $h\tau\tau \propto c_2 = -\sin \alpha / \cos \beta$

has a top-phobic limit

Leptonic: $h\bar{t}t$, $h\bar{b}b \propto c_1$; $h\tau\tau \propto c_2$ has a tau-phobic limit

Flipped: $h\bar{t}t$, $h\tau\tau \propto c_1$; $h\bar{b}b \propto c_2$ has a bottom-phobic limit

Can do 2-parameter fits within the model
(or 3-parameter, including new loop contribution to $h\gamma\gamma$);
test relative consistency of different model coupling patterns.
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):

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

Each rate depends on multiple couplings. → correlations
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):

$$\sigma_i = \overline{g}_i^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_j = \overline{g}_j^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum_{\text{SM}} \overline{g}_k^2 \Gamma_{k}^{\text{SM}} + \sum_{\text{new}} \Gamma_{k}^{\text{new}}$$

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 \( a \):

\[
\text{Rate}_{ij} = a^2 \sigma_i^{SM} \frac{a^2 \Gamma_{j}^{SM}}{a^2 \Gamma_{tot}^{SM} + \Gamma_{\text{new}}}
\]

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 \( \Gamma_{tot} > \) expt. resolution; \( \Gamma_{tot}^{SM} \approx 4 \) 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.)
How to think about the fit

First consider VBF → h → WW:
- Rate = \( \sigma(\text{VBF} \rightarrow h) \times \text{BR}(h \rightarrow WW) \).
- use the fact that \( \text{BR}(h \rightarrow WW) \leq 1 \).
  (can include other measured decays in VBF channels to tighten this)
- VBF → h → WW rate then puts a lower bound on \( \sigma(\text{VBF} \rightarrow h) \).
- This puts a lower bound on the \( hWW, hZZ \) couplings.
- Calculate lower bound on \( \Gamma(h \rightarrow WW, ZZ) \) to get a lower bound on \( \Gamma_{\text{tot}} \).

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 \( \sigma(\text{VBF} \rightarrow h) \).
- VBF → h → WW rate puts a lower bound on \( \text{BR}(h \rightarrow WW) \).
- Calculate theoretical upper bound on \( \Gamma(h \rightarrow WW) \) to get an upper bound on \( \Gamma_{\text{tot}} \). \( \Gamma_{\text{tot}} \geq \Gamma(h \rightarrow WW, ZZ) \)
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


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

GF $gg \rightarrow H \rightarrow WW$
VBF $qqH \rightarrow qqWW$
$tt\bar{H}, \ H \rightarrow WW$

GF $gg \rightarrow H \rightarrow ZZ$
VBF $qqH \rightarrow qqZZ$

VBF $qqH \rightarrow qq\tau\tau$

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

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 $qqH \rightarrow qqWW$

$tt\bar{H}, H \rightarrow WW$

GF $gg \rightarrow H \rightarrow ZZ$

VBF $qqH \rightarrow qqZZ$

VBF $qqH \rightarrow qq\tau\tau$

Inclusive $H \rightarrow \gamma\gamma$

VBF $qqH \rightarrow qq\gamma\gamma$

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

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

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

$tt\bar{H}, H \rightarrow b\bar{b} \times 50\%$ vs. 2004 study

$WH/ZH, H \rightarrow b\bar{b}$ a la Butterworth

All expt numbers from 14 TeV “first 30 fb$^{-1}$” studies.
\[ \Delta \bar{g}_W^2, \Delta \bar{g}_Z^2 \sim 35\% \rightarrow 25\% \]
\[ \Delta \bar{g}_b^2 \sim 65\% \rightarrow 45\% \]
\[ \Delta \bar{g}_t^2 \sim 60\% \rightarrow 35\% \]
\[ \Delta \bar{g}_T^2 \sim 40\% \rightarrow 25\% \]

for 125 GeV Higgs

\[ \bar{g}_W = \bar{g}_Z \leq 1 \]
\[ \Gamma_{\text{unobs}} \leq 50\% \rightarrow 35\% \text{ of } \Gamma_{\text{tot,fit}} \]

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

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

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Higgs boson

UdeM/McGill Feb 2013
- Much more sophisticated statistical analysis (SFitter)
- Assume no “unexpected” decays

$g_i = g_i^{SM}(1 + \Delta_i)$: 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)
\[ \Delta_W: \pm 24\% \quad \Delta_Z: \pm 31\% \]
\[ \Delta_t: \pm 53\% \quad \Delta_b: \pm 44\% \quad \Delta_\tau: \pm 31\% \]  
(SM-decays-only constraint
\[ \Delta_g: \pm 61\% \quad \Delta_\gamma: \pm 31\% \]  
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 Lafayette 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?
\[ \sigma(A \rightarrow h) \ast BR(H \rightarrow X) \propto \Gamma_A \Gamma_X / \Gamma_{\text{tot}} \]
\[ \Gamma_W / \sqrt{\Gamma_{\text{tot}}}; \Gamma_Z / \sqrt{\Gamma_{\text{tot}}} \]
\[ \Gamma_t / \sqrt{\Gamma_{\text{tot}}}; \Gamma_b / \sqrt{\Gamma_{\text{tot}}}; \Gamma_{\tau} / \sqrt{\Gamma_{\text{tot}}} \]
\[ \Gamma_g / \sqrt{\Gamma_{\text{tot}}}; \Gamma_{\gamma} / \sqrt{\Gamma_{\text{tot}}} \]

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

- Always need to input a theory assumption because of $\Gamma_{\text{unobs}}$.
[Can we measure $h \rightarrow$ 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 4\(f\) final states from \(WW\) and \(ZZ\) decays non-negligible below \(WW\) threshold.

- EW RCs to \(h \rightarrow WW\) introduce dependence on \(y_t\).

- Nonstandard production modes like \(b\bar{b} \rightarrow h\).

- \(\sigma(A \rightarrow h)\times BR(H \rightarrow X) \propto \Gamma_A\Gamma_X/\Gamma_{\text{tot}}\) 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 $\rightarrow$ variation with $M_h$ is due to kinematics.

1 GeV uncertainty in $M_h \Rightarrow 5\%$ uncertainty in $\bar{g}_b/\bar{g}_W$.
100 MeV uncertainty in $M_h \Rightarrow 0.5\%$ uncertainty in $\bar{g}_b/\bar{g}_W$.
$M_h$ could be included as a correlated fit parameter.
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?
The Carleton Theory Group wants YOU!

Openings for up to 3 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*