Prospects for Higgs coupling extraction from LHC

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Higgs: Now and in the Future
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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: $g_Z \equiv \sqrt{g^2 + g'^2}$, $v = 246$ GeV

$$\mathcal{L} = |\mathcal{D}_\mu H|^2 \;\rightarrow\; (g^2/4)(h+v)^2 W^+ W^- + (g_Z^2/8)(h+v)^2 ZZ$$

$$M_W^2 = g^2 v^2/4 \qquad hWW:\; i(g^2 v/2) g^{\mu\nu}$$

$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ:\; i(g_Z^2 v/2) g^{\mu\nu}$$

Fermions:

$$\mathcal{L} = -y_f \bar{f}_R H^\dagger Q_L + \cdots \;\rightarrow\; -(y_f/\sqrt{2})(h+v)\bar{f}_R f_L + \text{h.c.}$$

$$m_f = y_f v/\sqrt{2} \qquad h\bar{f}f:\; i m_f/v$$

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. $v \equiv \sqrt{v_1^2 + v_2^2}$, $\phi_v = \frac{v_1}{v} h_1 + \frac{v_2}{v} h_2$

$$\mathcal{L} = |\mathcal{D}_\mu H_1|^2 + |\mathcal{D}_\mu H_2|^2$$

$$M_W^2 = g^2 v^2/4 \qquad hWW: \; i\langle h|\phi_v\rangle (g^2 v/2) g^{\mu\nu} \equiv i\bar{g}_W (g^2 v/2) g^{\mu\nu}$$

$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ: \; i\langle h|\phi_v\rangle (g_Z^2 v/2) g^{\mu\nu} \equiv i\bar{g}_Z (g^2 v/2) g^{\mu\nu}$$

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). $Q = T^3 + Y/2$

$$\mathcal{L} \supset |\mathcal{D}_\mu \Phi|^2 \;\to\; (g^2/4)[2T(T+1) - Y^2/2](\phi + v)^2 W^+ W^- + (g_Z^2/8) Y^2 (\phi + v)^2 ZZ$$

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

Tightly constrained by ρ 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:

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

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

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

$\Rightarrow$ 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):

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

Each rate depends on multiple couplings. → correlations

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$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum_{\text{SM}} \bar{g}_k^2 \Gamma_k^{\text{SM}} + \sum_{\text{new}} \Gamma_k^{\text{new}}$$

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., $h \to$ 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:

$$\text{Rate}_{ij} = a^2 \sigma_i^{\text{SM}} \frac{a^2 \Gamma_j^{\text{SM}}}{a^2 \Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{new}}}$$

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 $\Gamma_{\text{tot}} >$ expt. resolution;
  $\Gamma_{\text{tot}}^{\text{SM}} \simeq 4$ MeV for 125 GeV Higgs)

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

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

How to think about the fit

First consider VBF $\to h \to WW$:

- Rate $= \sigma(\text{VBF} \to h) \times \text{BR}(h \to WW)$.
- use the fact that $\text{BR}(h \to WW) \leq 1$.

  (can include other measured decays in VBF channels to tighten this)
- VBF $\to h \to WW$ rate then puts a lower bound on $\sigma(\text{VBF} \to h)$.
- This puts a lower bound on the hWW, hZZ couplings.
- Calculate lower bound on $\Gamma(h \to WW, ZZ) \to$ get a lower bound on Γ_{tot}.

$\Gamma_{\text{tot}} \geq \Gamma(h \to WW, ZZ)$

Theory assumption that $\bar{g}_W \leq 1$ and $\bar{g}_Z \leq 1$: $\Leftarrow$!

(i.e., assume hWW and hZZ couplings are no larger than in SM)

- Imposes a theoretical upper bound on $\sigma(\text{VBF} \to h)$.
- VBF $\to h \to WW$ rate puts a lower bound on $\text{BR}(h \to WW)$.
- Calculate theoretical upper bound on $\Gamma(h \to WW) \to$ get an upper bound on Γ_{tot}.

$\Gamma_{\text{tot}} = \Gamma(h \to WW)/\text{BR}(h \to WW)$

How to think about the fit

Now include the other measurements.

$$\frac{\text{Rate}(A \to X)}{\text{Rate}(A \to Y)} = \frac{\sigma(A \to h)\Gamma(h \to X)/\Gamma_{\text{tot}}}{\sigma(A \to h)\Gamma(h \to Y)/\Gamma_{\text{tot}}} \Rightarrow \frac{\bar{g}_X^2}{\bar{g}_Y^2}$$

$$\frac{\text{Rate}(A \to X)}{\text{Rate}(B \to X)} = \frac{\sigma(A \to h)\Gamma(h \to X)/\Gamma_{\text{tot}}}{\sigma(B \to h)\Gamma(h \to X)/\Gamma_{\text{tot}}} \Rightarrow \frac{\bar{g}_A^2}{\bar{g}_B^2}$$

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

Feed back other fitted couplings into Γ_{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

Zeppenfeld, Kinnunen, Nikitenko, Richter-Was, PRD62, 013009 (2000); Les Houches 1999

Add $t\bar{t}h$, $h \to \tau\tau$ 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)

More careful analysis of probability density and correlations, using updated expt studies. Assume no unexpected decay channels.

$M_h = 120$ GeV Lafaye, Plehn, Rauch, D. Zerwas, & Dührssen, JHEP0908, 009 (2009)

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

Dührssen, Heinemeyer, HEL, Rainwater, Weiglein, & Zeppenfeld, PRD70, 113009 (2004)

GF $gg \to H \to WW$
VBF $qqH \to qqWW$
$t\bar{t}H$, $H \to WW$

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

VBF $qqH \to qq\tau\tau$

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

$t\bar{t}H$, $H \to b\bar{b}$ ⇐!!

All expt numbers from 14 TeV “first 30 fb^{-1}” studies.

Higgs channels used (2009 study, 120 GeV):

Lafaye, Plehn, Rauch, D. Zerwas, & Dührssen, JHEP 0908, 009 (2009)

GF $gg \to H \to WW$
VBF $qqH \to qqWW$
$t\bar{t}H$, $H \to WW$

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

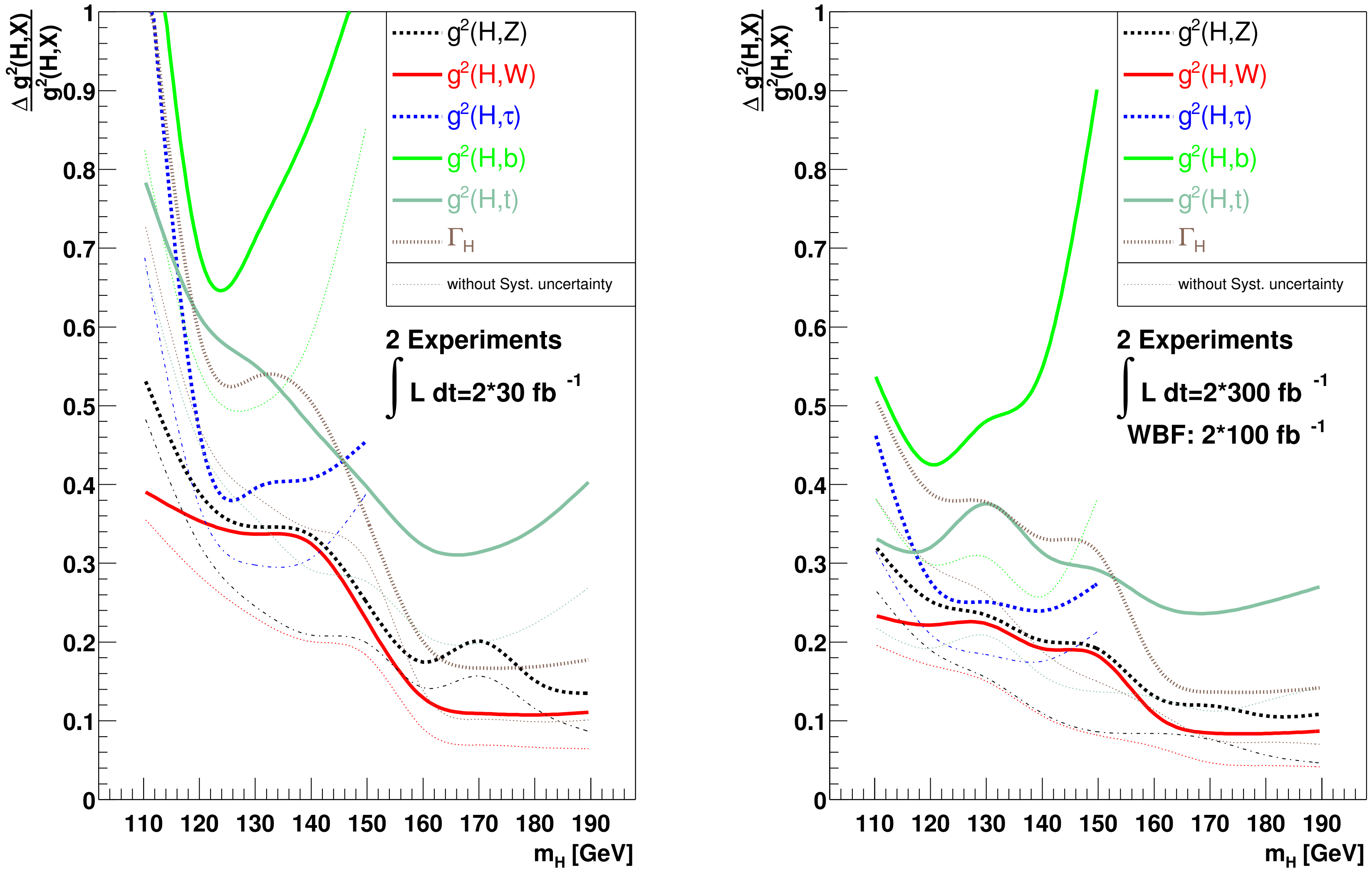
VBF $qqH \to qq\tau\tau$

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

$t\bar{t}H$, $H \to b\bar{b}$ ×50% vs. 2004 study
WH/ZH, $H \to b\bar{b}$ a la Butterworth

All expt numbers from 14 TeV “first 30 fb^{-1}” studies.

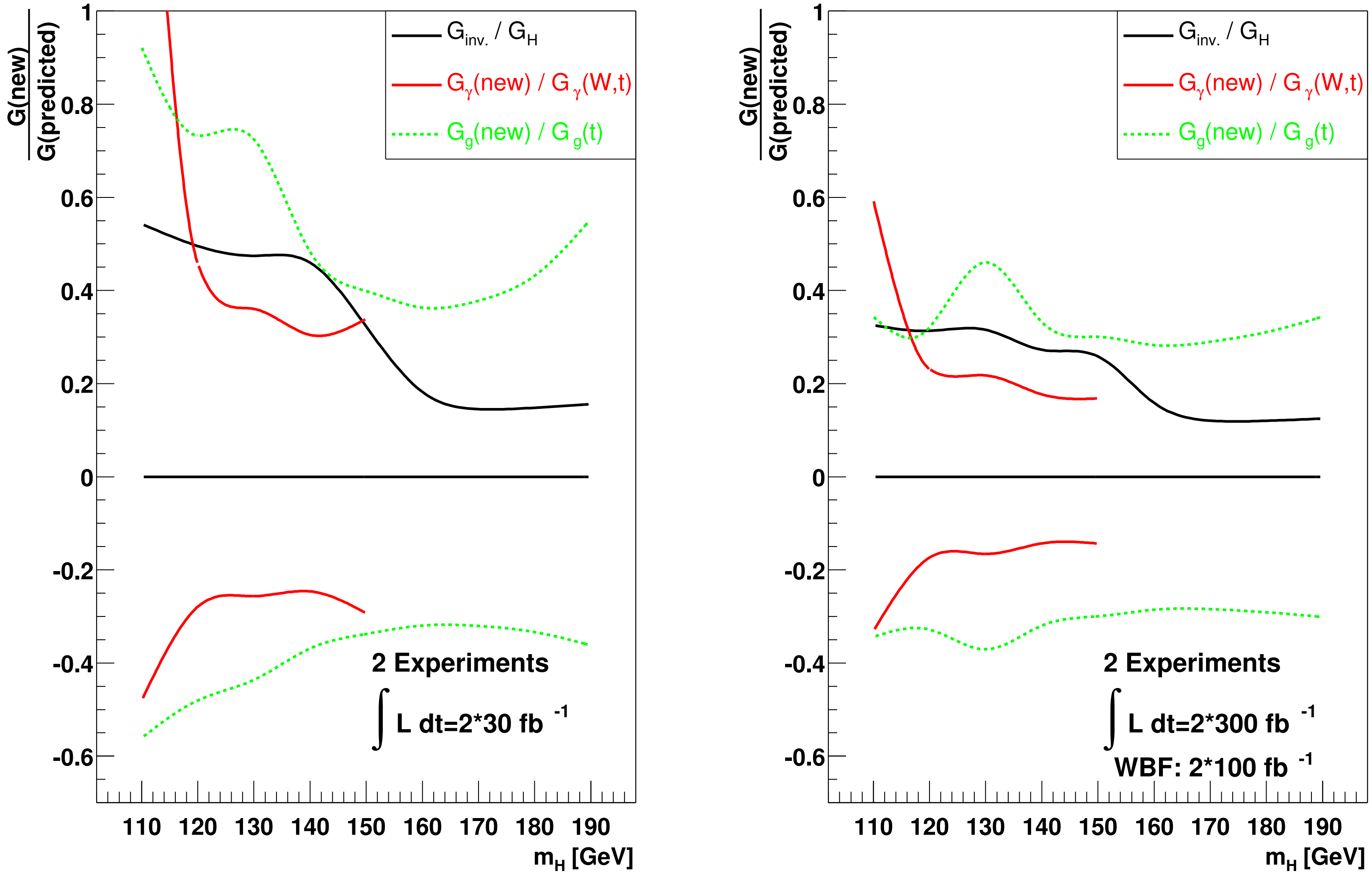
Dührssen, Heinemeyer, HEL, Rainwater, Weiglein, & Zeppenfeld, PRD70, 113009 (2004)



$\Delta\bar{g}^2_{W,Z} \sim 35\% \to 25\%$ $\Delta\bar{g}^2_t \sim 60\% \to 35\%$ for 125 GeV Higgs

$\Delta\bar{g}^2_b \sim 65\% \to 45\%$ $\Delta\bar{g}^2_\tau \sim 40\% \to 25\%$ $\bar{g}_W = \bar{g}_Z \leq 1$

Dührssen, Heinemeyer, HEL, Rainwater, Weiglein, & Zeppenfeld, PRD70, 113009 (2004)



$\Gamma_{\text{unobs}} \leq 50\% \to 35\%$ of $\Gamma_{\text{tot,fit}}$ for 125 GeV Higgs

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

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

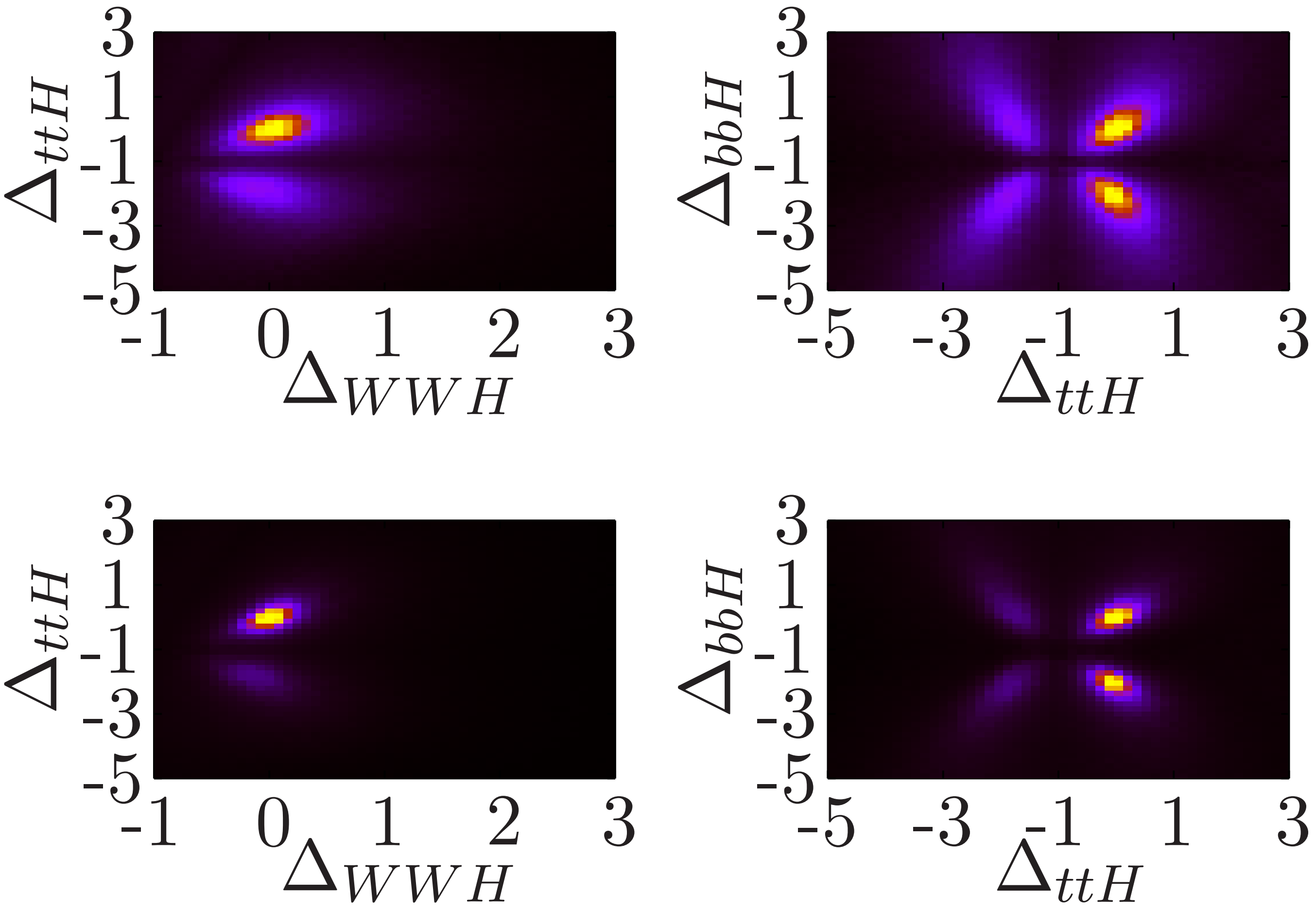
Lafaye, Plehn, Rauch, D. Zerwas, & Dührssen, JHEP 0908, 009 (2009)

- 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}

300 fb^{-1}

Lafaye, Plehn, Rauch, D. Zerwas, & Dührssen, JHEP 0908, 009 (2009)

30 fb^{-1}, extracted error: (caution: non-Gaussian)

$\Delta_W : \pm 24\%$ $\Delta_Z : \pm 31\%$ compare 35-65% on $\Delta \bar{g}^2$

$\Delta_t : \pm 53\%$ $\Delta_b : \pm 44\%$ $\Delta_\tau : \pm 31\%$ (SM-decays-only constraint

$\Delta_g : \pm 61\%$ $\Delta_\gamma : \pm 31\%$ less restrictive than $\bar{g}_{W,Z} \leq 1$)

30 fb^{-1}, extracted error on ratios:

$\Delta_Z/\Delta_W : \pm 41\%$

$\Delta_t/\Delta_W : \pm 51\%$ $\Delta_b/\Delta_W : 31\%$ $\Delta_\tau/\Delta_W : 28\%$

$\Delta_g/\Delta_W : \pm 61\%$ $\Delta_\gamma/\Delta_W : 30\%$

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?

$h \to b\bar{b}$ channel(s) are critical.

- Largest Higgs BR at $\sim$ 125 GeV: crucial for constraining $\Gamma_{\rm tot}$.
- Boosted-object $Wh/Zh,\ h \to b\bar{b}$ [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?

$\sigma(A \to h) * \mathrm{BR}(H \to X) \propto \Gamma_A \Gamma_X / \Gamma_{\mathrm{tot}}$

$\Gamma_W/\sqrt{\Gamma_{\mathrm{tot}}}$; $\Gamma_Z/\sqrt{\Gamma_{\mathrm{tot}}}$

$\Gamma_t/\sqrt{\Gamma_{\mathrm{tot}}}$; $\Gamma_b/\sqrt{\Gamma_{\mathrm{tot}}}$; $\Gamma_\tau/\sqrt{\Gamma_{\mathrm{tot}}}$

$\Gamma_g/\sqrt{\Gamma_{\mathrm{tot}}}$; $\Gamma_\gamma/\sqrt{\Gamma_{\mathrm{tot}}}$

- Theoretically-inspired parameterization:

$\bar{g}_W$, $\bar{g}_Z$, $\bar{g}_t$, $\bar{g}_b$, $\bar{g}_\tau$: need unambiguous definitions at NLO

$\Gamma_{g,\mathrm{new}}$, $\Gamma_{\gamma,\mathrm{new}}$: BSM particles in gg, $\gamma\gamma$ loops

Γ_{invis} (use dedicated $h \to$ invisible channels)

Γ_{unobs} (includes $c\bar{c}$, gg, light q jets, etc.)

- Always need to input a theory assumption because of Γ_{unobs}.

[Can we measure $h \to$ jets? Boosted object techniques?]

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.

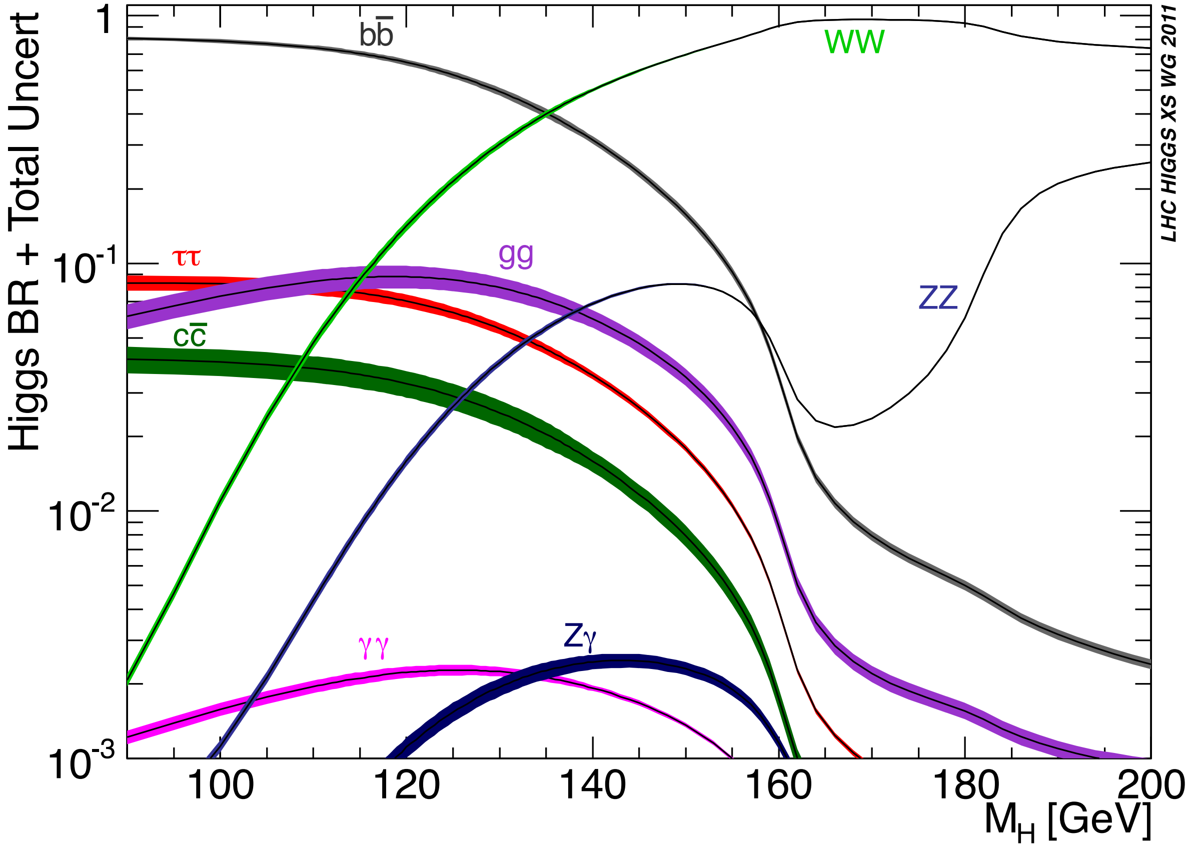
- EW RCs to $h \to WW$ introduce dependence on y_t.

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

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



1 GeV uncertainty in M_h ⇒ 5% uncertainty in $\bar{g}_b/\bar{g}_W$.
100 MeV uncertainty in M_h ⇒ 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, τ, 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 4 M.Sc. or Ph.D. students starting September 2012

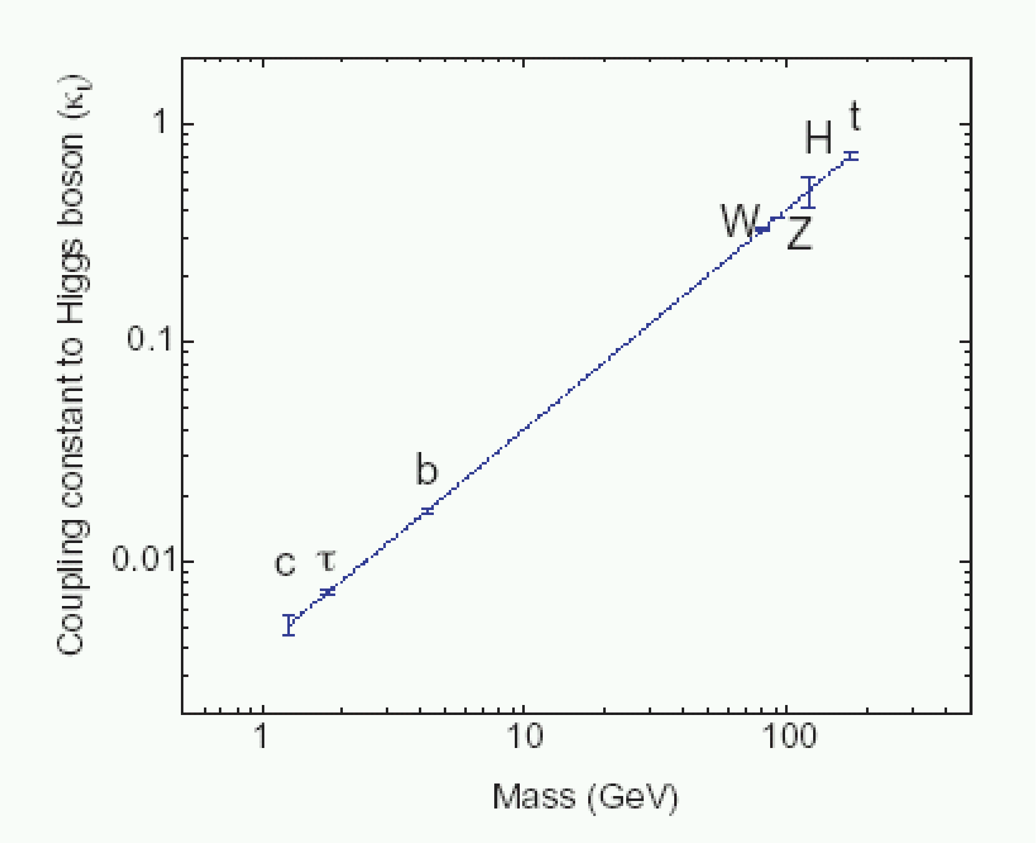
Work on LHC phenomenology and model building with Profs. Steve Godfrey or Thomas Grégoire

BACKUP SLIDES

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