The Higgs boson: where we go from here

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U. de Montréal Feb 19, 2013

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Outline

Introduction: a long-expected particle

Higgs discovery and current status

Higgs measurements: what we hope to learn
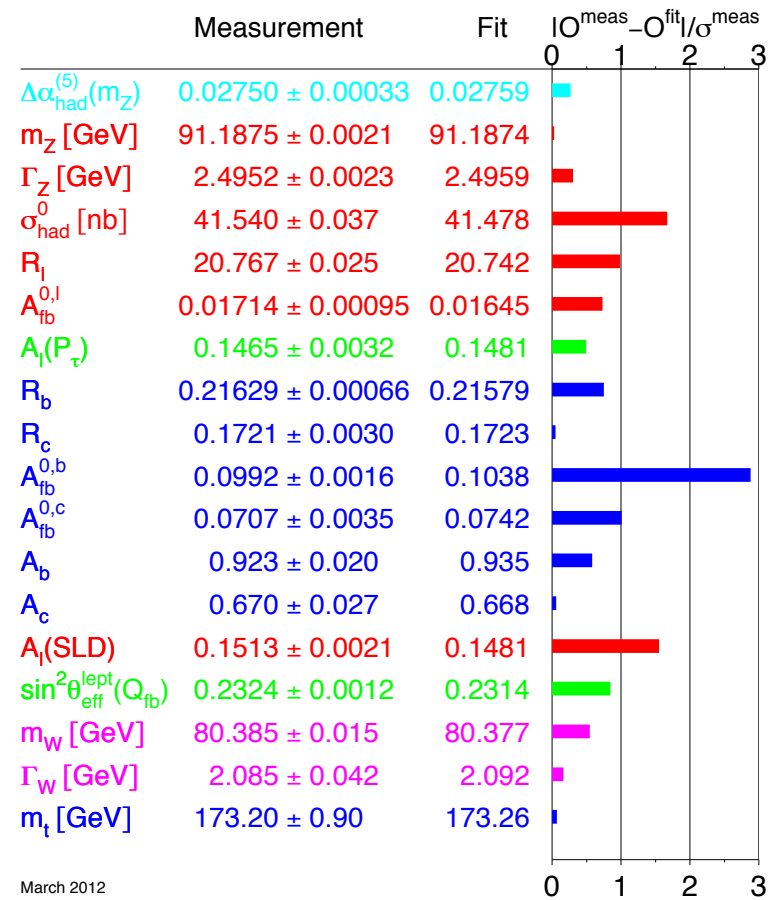
Experimental prospects

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, α_{EM}, G_F); predict all other observables. Works very well.

	Measurement	Fit	$|O^{meas} - O^{fit}|/\sigma^{meas}$
			0 1 2 3
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.385 ± 0.015	80.377	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.20 ± 0.90	173.26	

March 2012

0   1   2   3

LEP Electroweak WG, Winter 2012

Spontaneously broken electroweak theory can be described by a Chiral Lagrangian (with no reference to a Higgs).

The pure electroweak theory looks like this:

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

- 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)

Put in a gauge-kinetic term for Σ and interactions with fermions:

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

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

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

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

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

σ^a are the three Pauli spin matrices.

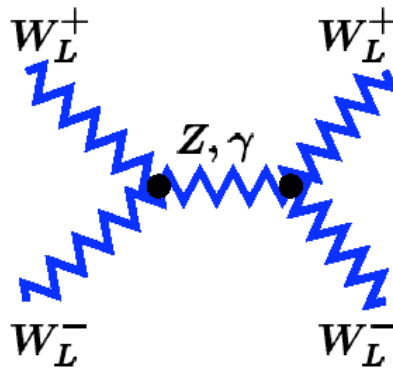- The ξ^a degrees of freedom correspond to the third polarization states of the massive W and Z.

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.
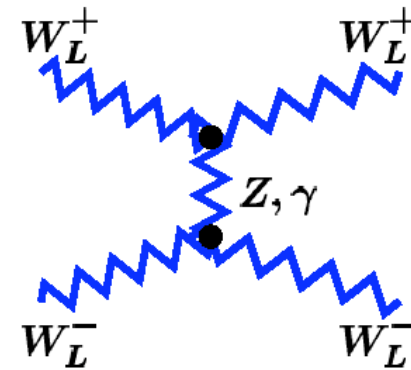
Scattering of longitudinally-polarized Ws

SU(2) x U(1) @ E^4

W_L^+ W_L^+ W_L^+ W_L^+ W_L^+ W_L^+

Z, γ Z, γ

W_L^- W_L^- W_L^- W_L^- W_L^- W_L^-
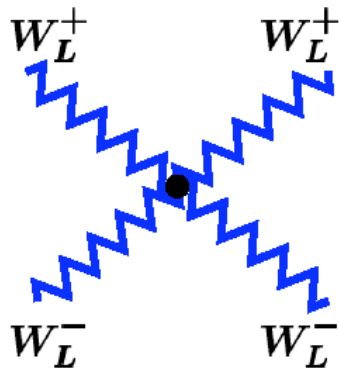
(a)   (b)   (c)

Graphs	$g^2 \dfrac{E^4}{m_w^4}$
(a)	$-3 + 6\cos\theta + \cos^2\theta$
(b)	$-4\cos\theta$
(c)	$+3 - 2\cos\theta - \cos^2\theta$
Sum	0

$$\epsilon_L^\mu(k) = \frac{k^\mu}{m_w} + \mathcal{O}\left(\frac{m_w}{E}\right)$$

Graphics from R.S. Chivukula, LHC4ILC 2007

Scattering of longitudinally-polarized Ws exposes need for a Higgs*

SU(2) x U(I) @ E^2
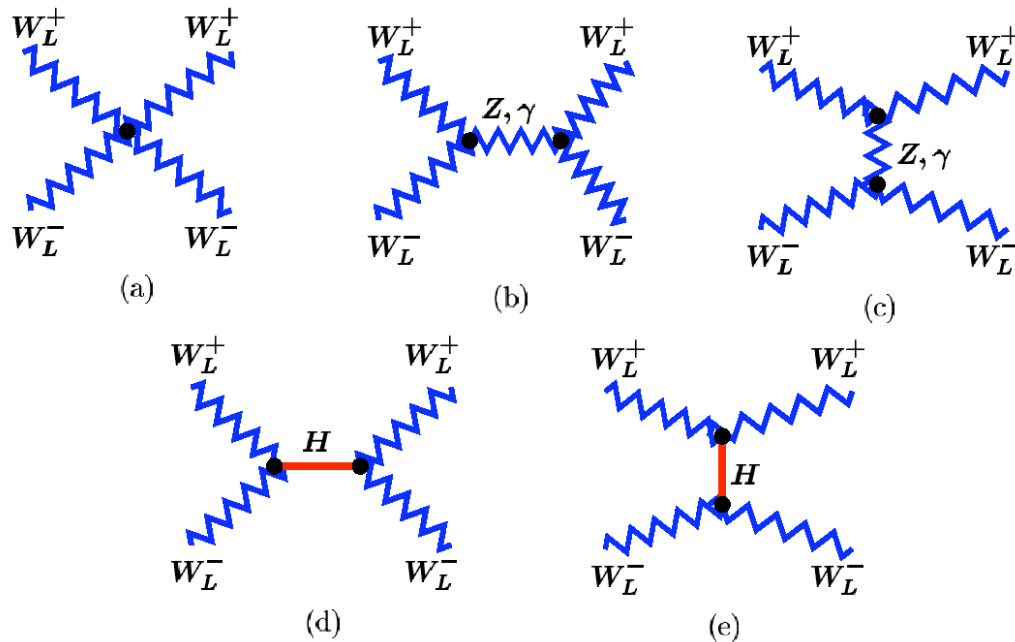
Graphs $\qquad g^2 \dfrac{E^2}{m_w^2}$

(a) $\qquad +2 - 6\cos\theta$

(b) $\qquad -\cos\theta$

(c) $\qquad -\dfrac{3}{2} + \dfrac{15}{2}\cos\theta$

(d + e) $\qquad -\dfrac{1}{2} - \dfrac{1}{2}\cos\theta$

► $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\,v \simeq 1.0\,\text{TeV}$

► If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{8\pi}\,v \simeq 1.2\,\text{TeV}$

Sum $\qquad\qquad$ 0

including (d+e)

Graphics from R.S. Chivukula, LHC4ILC 2007 $\qquad$ *or something to play its role

Σ 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:

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

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

$V_L V_L \to hh$ is unitarized if $b = a^2$

With $a = b = c = 1$, can absorb h into the Σ 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 <u>fixed</u> by the mass-generation mechanism.

W and Z: $\qquad\qquad\qquad\qquad\qquad\qquad g_Z \equiv \sqrt{g^2 + g'^2}, \ v = 246$ GeV

$$\mathcal{L} = |\mathcal{D}_\mu H|^2 \ \to \ (g^2/4)(h + v)^2 W^+ W^- + (g_Z^2/8)(h + v)^2 ZZ$$
$$M_W^2 = g^2 v^2/4 \qquad hWW : \ i(g^2 v/2)g^{\mu\nu}$$
$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ : \ i(g_Z^2 v/2)g^{\mu\nu}$$

Fermions:

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

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

The only undetermined parameter is the Higgs mass.

Predict SM Higgs production cross sections (as function of M_h)

$\sigma(pp \to H+X)$ [pb]

$\sqrt{s}$= 8 TeV

pp → H (NNLO+NNLL QCD + NLO EW)

pp → qqH (NNLO QCD + NLO EW)

pp → WH (NNLO QCD + NLO EW)

pp → ZH (NNLO QCD +NLO EW)

pp → ttH (NLO QCD)

M_H [GeV]

LHC HIGGS XS WG 2012

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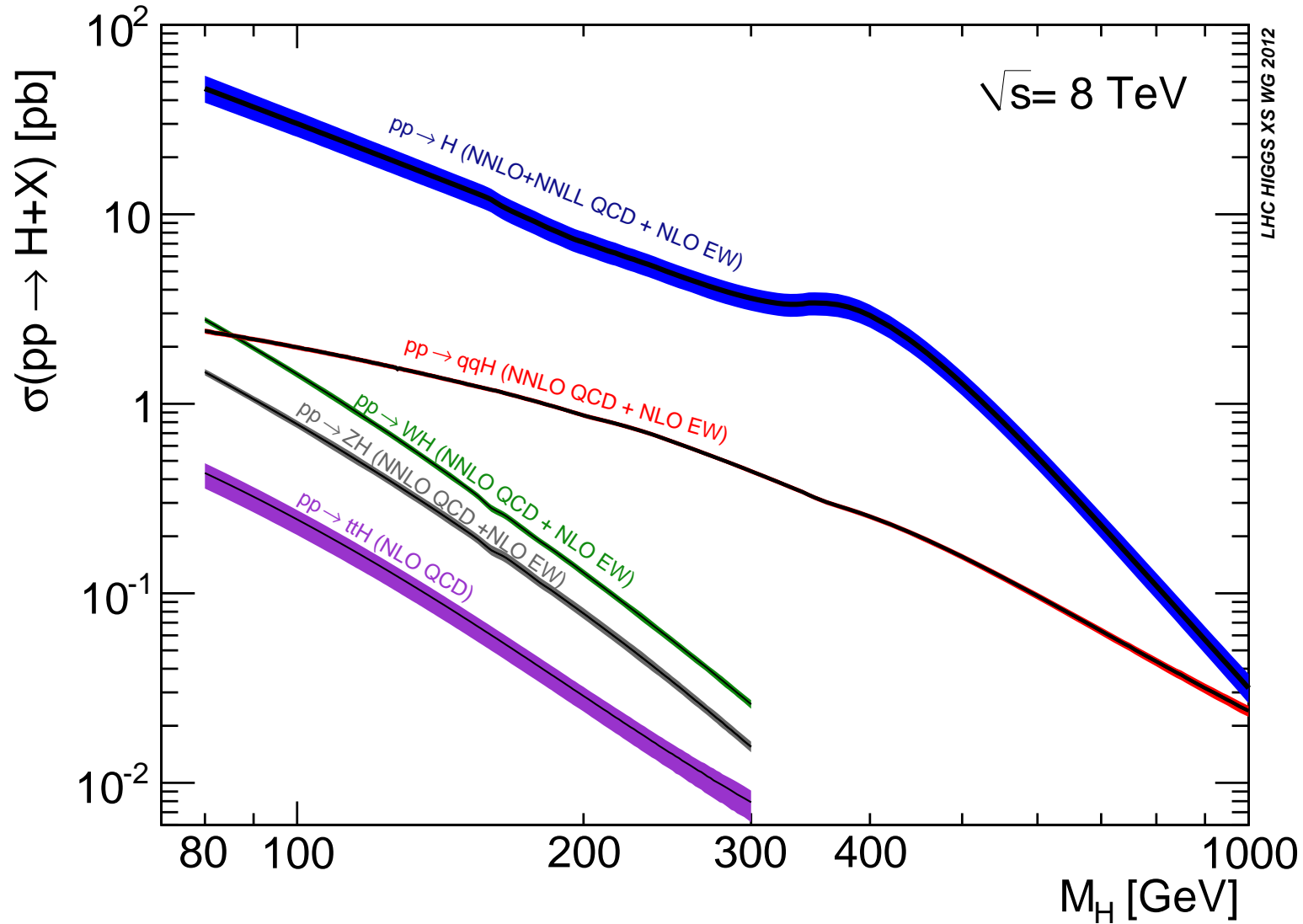
Predict SM Higgs decay branching ratios (as function of M_h)
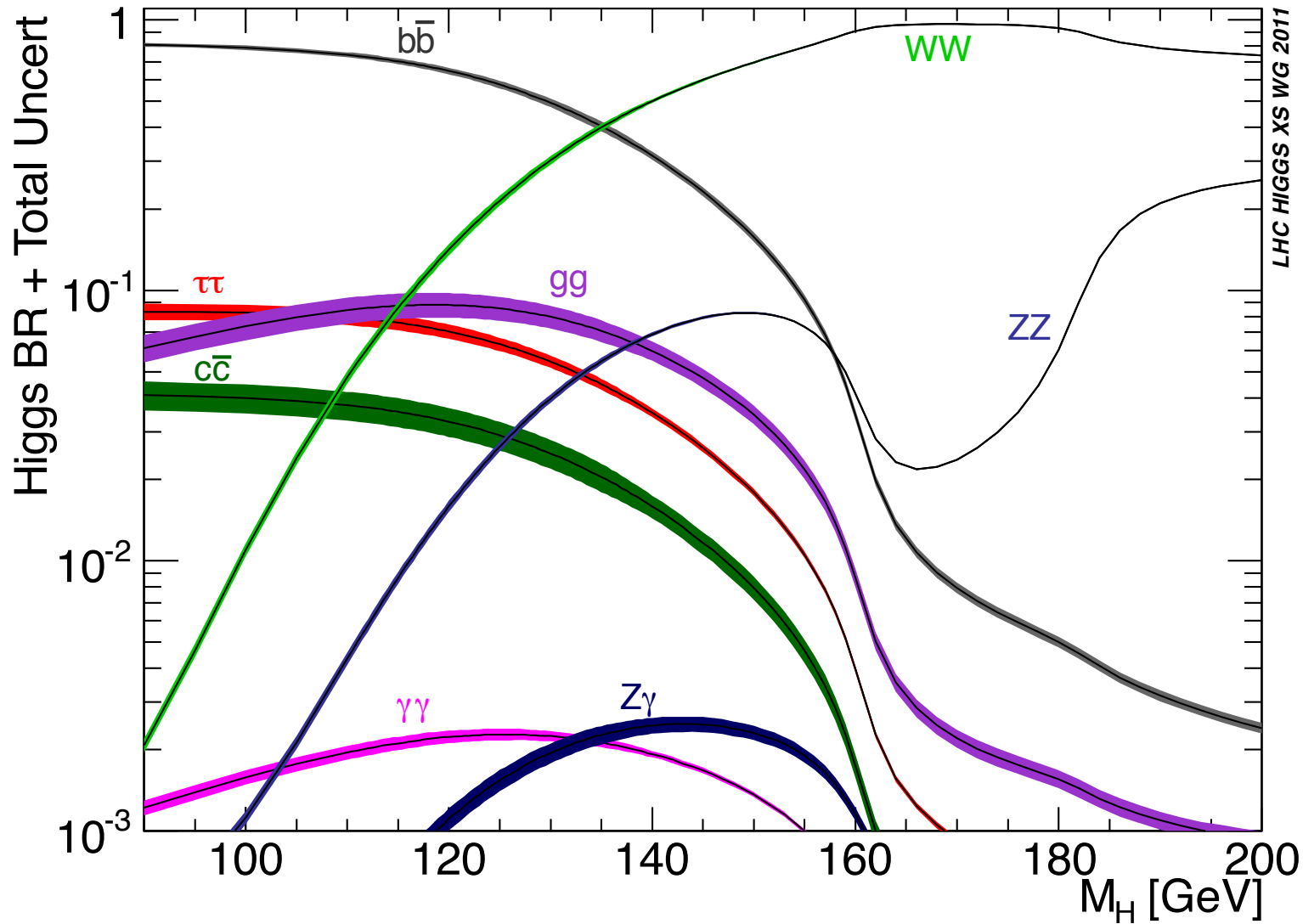
What is the Higgs mass?

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

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

Coupled channel analysis, $|\text{Re}\, a_0| \le 1/2$, $v \simeq 246$ 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 <u>one</u> remaining free parameter.
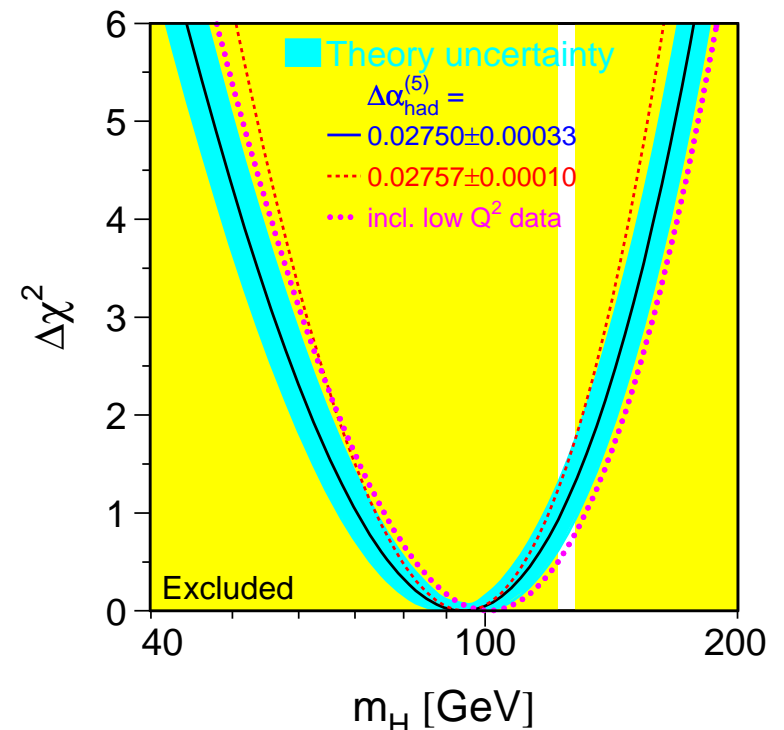
LEP Electroweak Working Group, Winter 2012
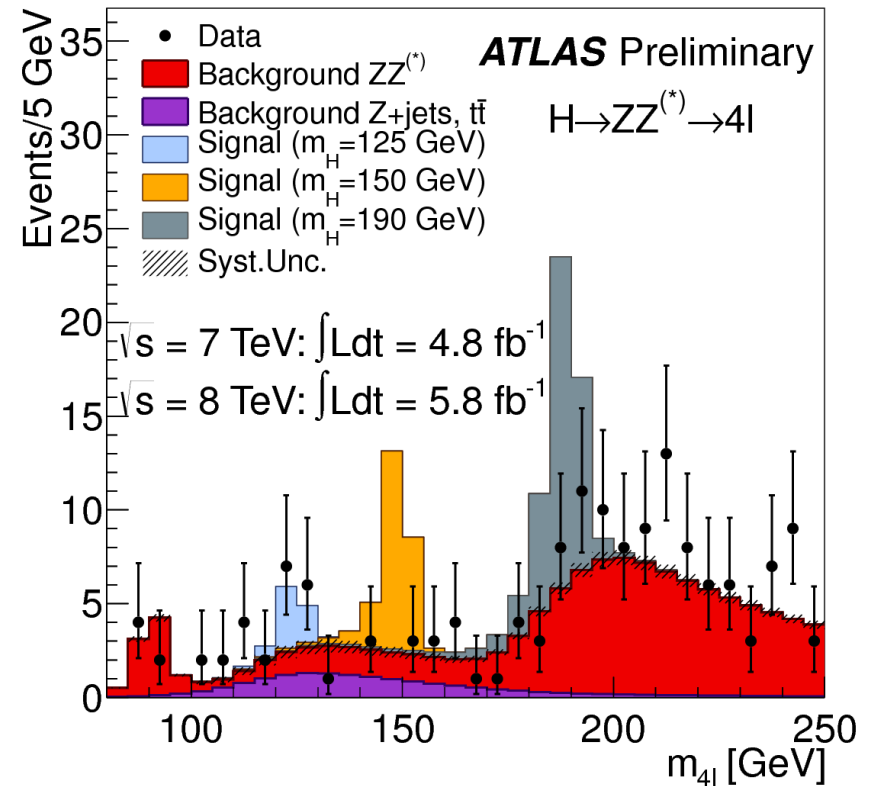
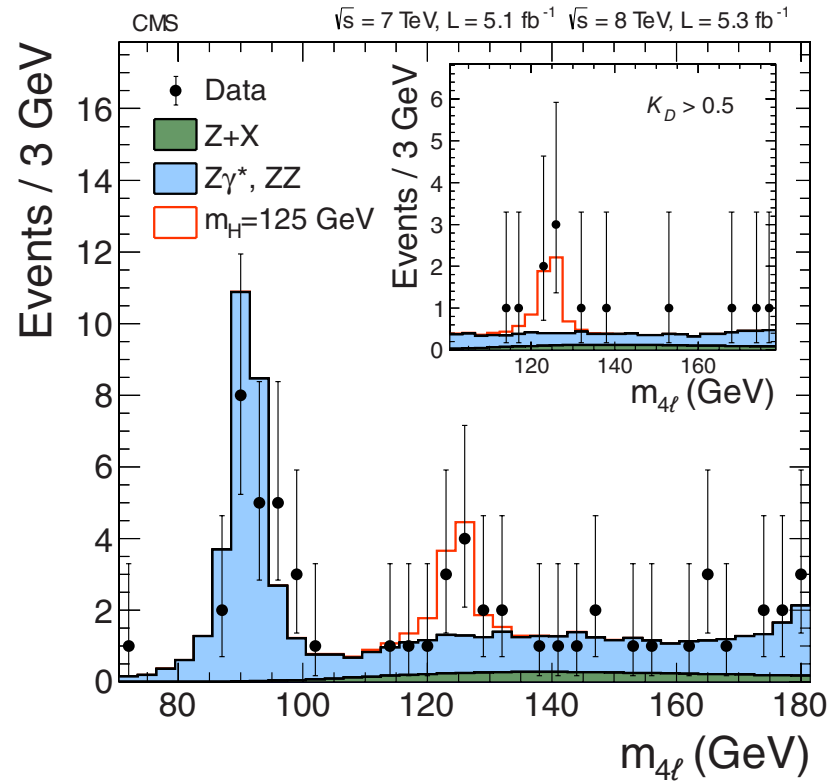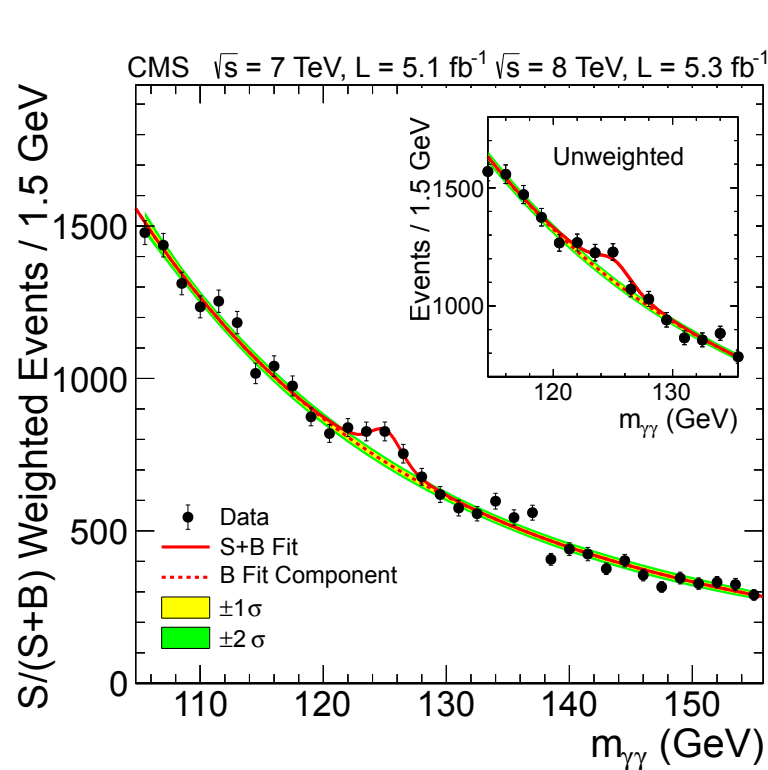*Heather Logan (Carleton U.)*   *Higgs boson*   *UdeM/McGill Feb 2013*

HIGGS DISCOVERY AND CURRENT STATUS

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

$h \to \gamma\gamma$ $h \to ZZ^* \to 4\ell$

ATLAS discovery plots, July 4, 2012

HIGGS DISCOVERY AND CURRENT STATUS

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

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$h \to ZZ^* \to 4\ell$

CMS discovery plots, July 4, 2012

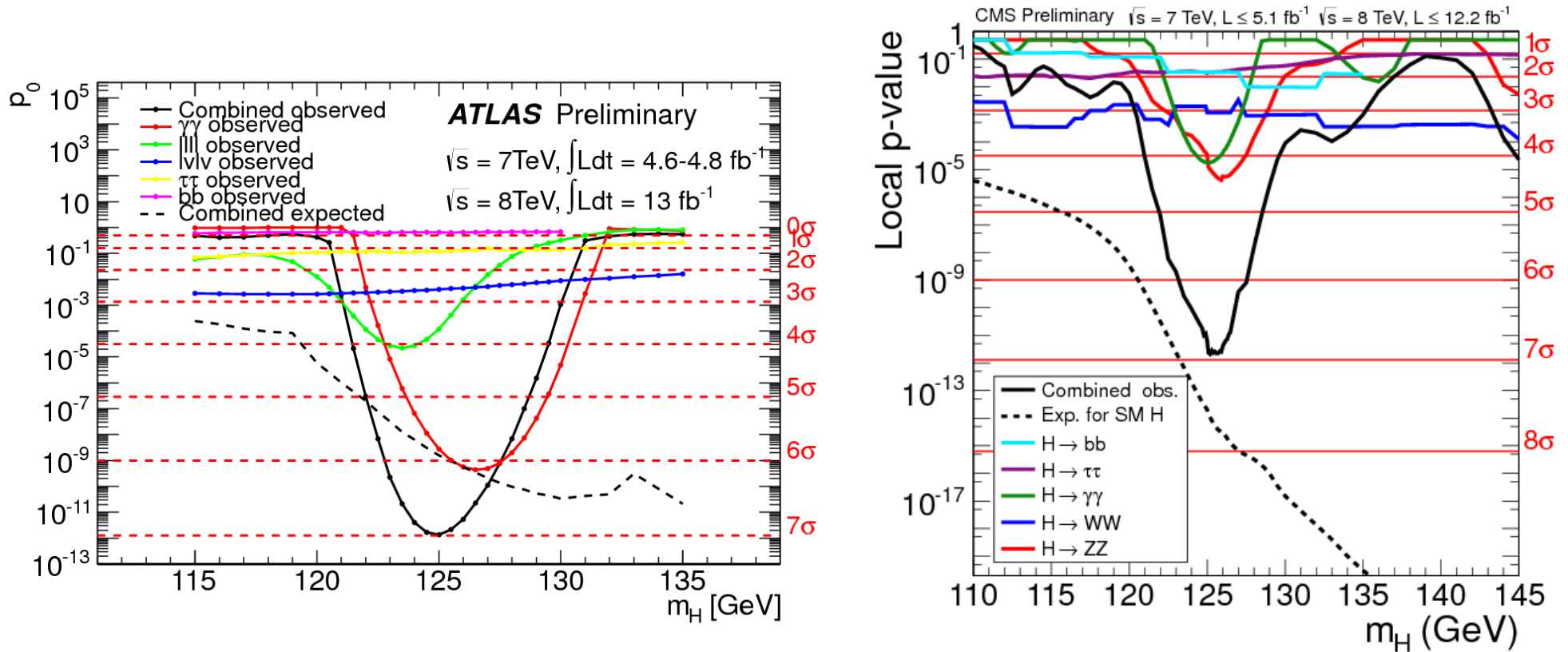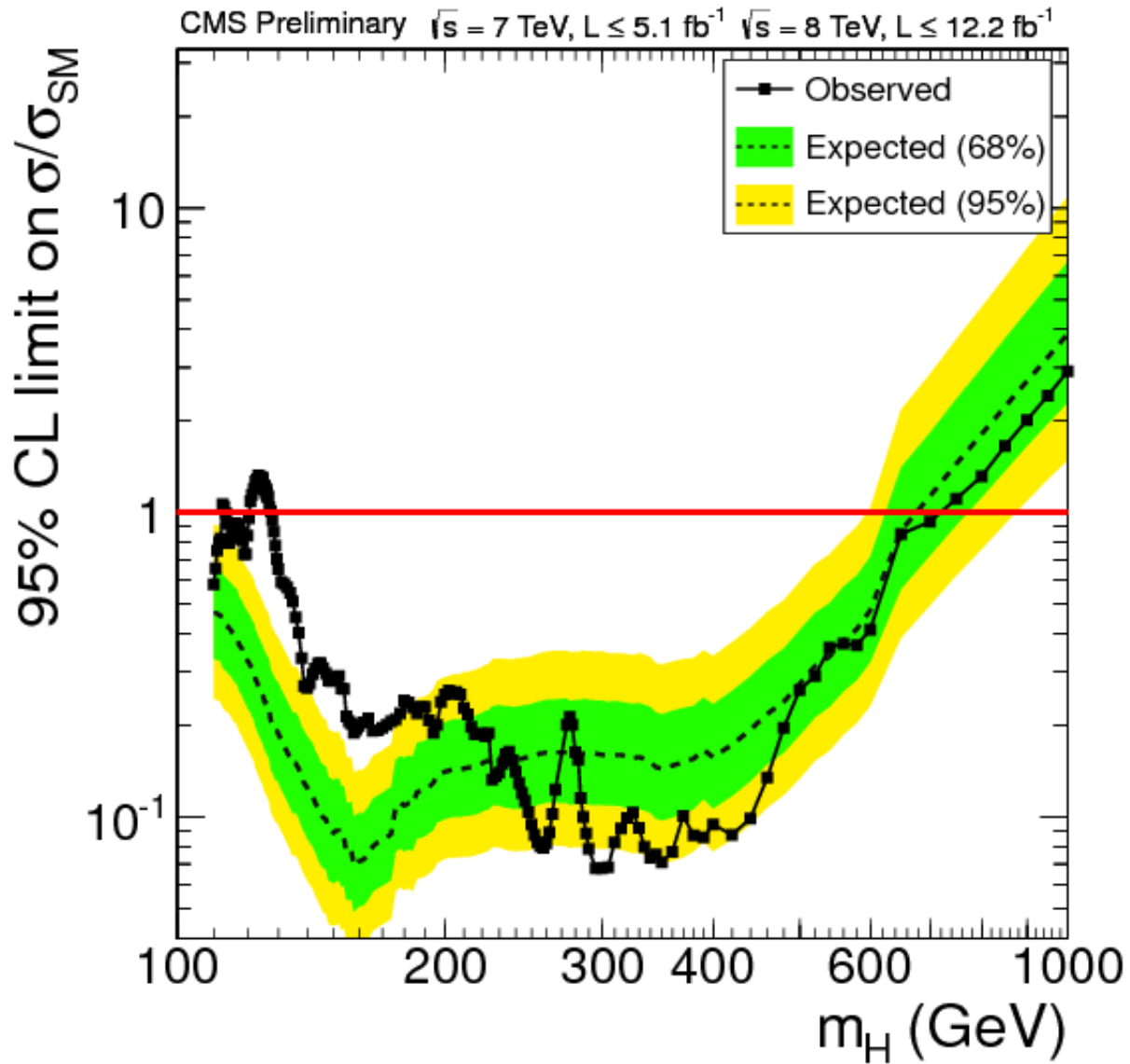More data collected and analyzed since then.

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

January 2013: 27 fb^{-1} collected per expt (7 and 8 TeV)
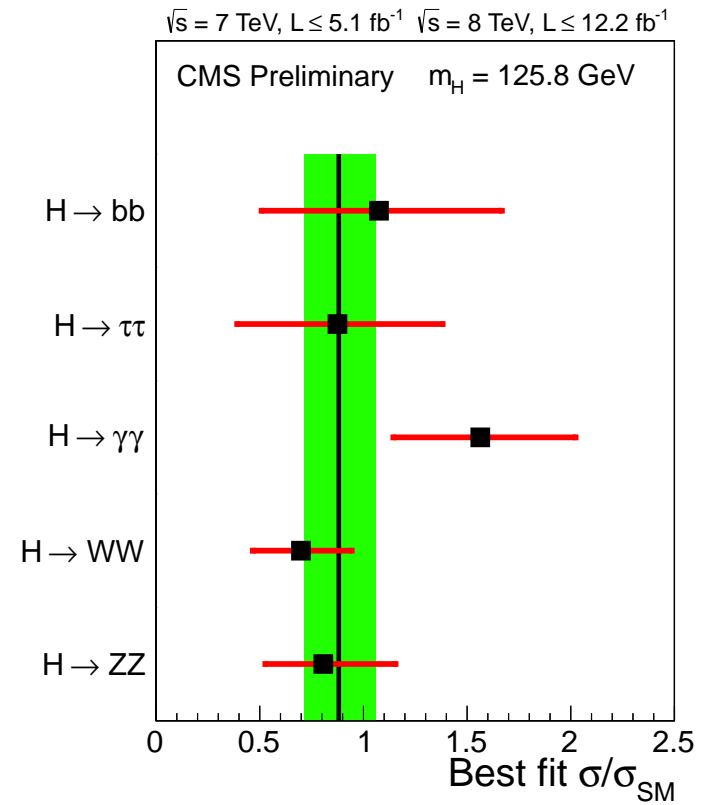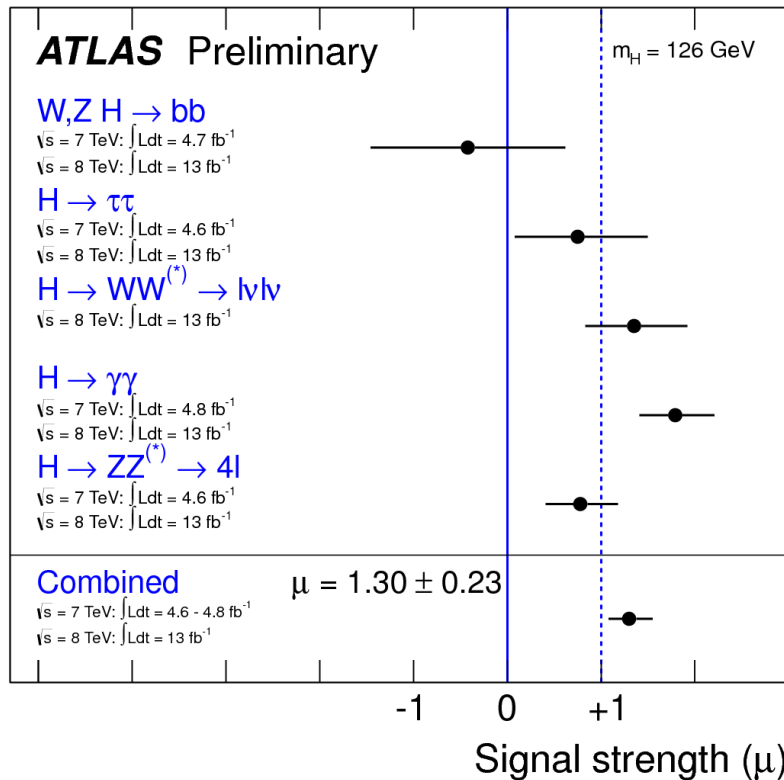Expect new analysis results for Moriond conferences (March)

No evidence for additional Higgs-like states.

HIGGS MEASUREMENTS: WHAT WE HOPE TO LEARN

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

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

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

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

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

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

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:

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

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

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 $h \to \gamma\gamma$ 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!

Higgs couplings <u>beyond</u> 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: $\sim 1 + \mathcal{O}(v^2/f^2)$

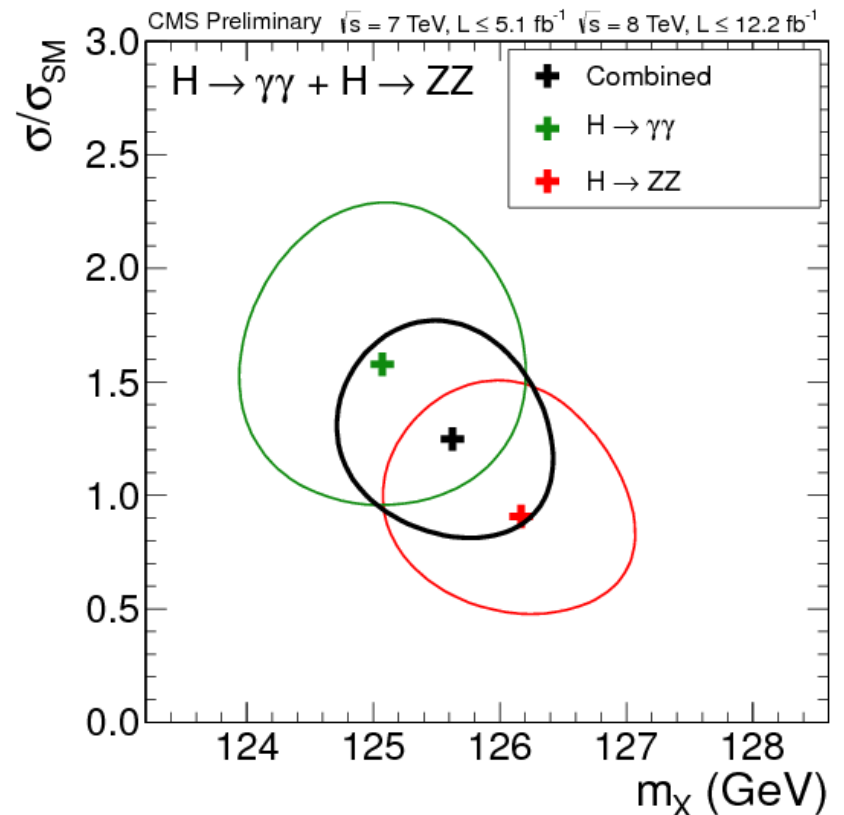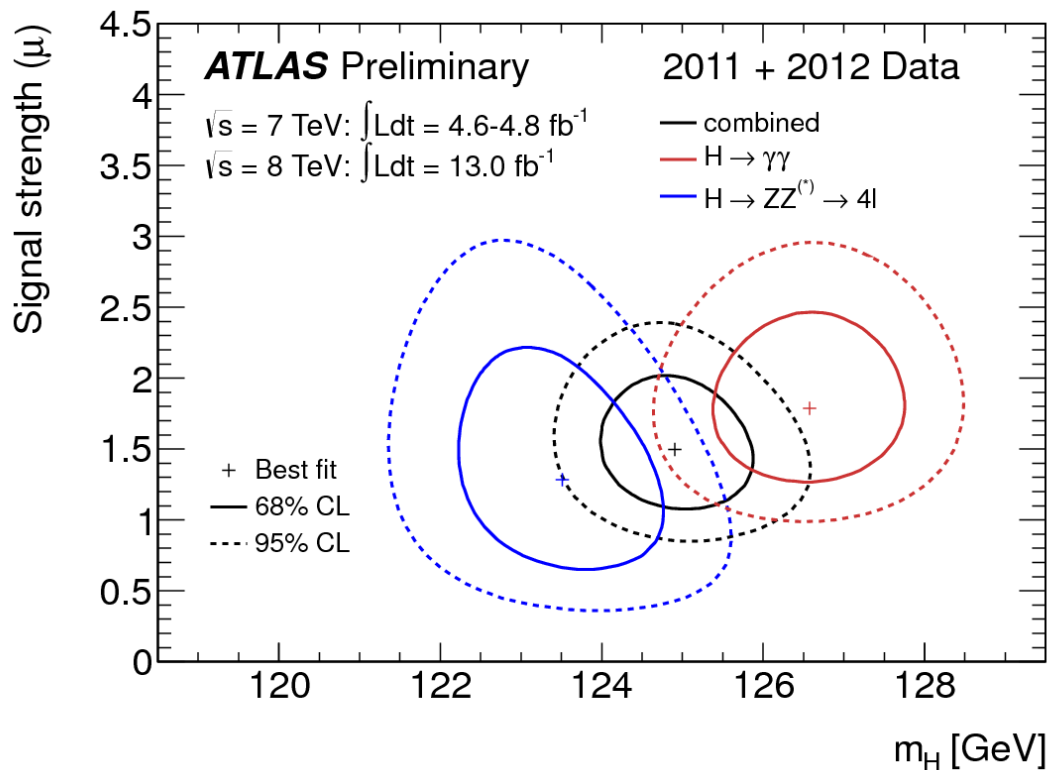 $f =$ scale of strong interactions; typically $f \gg v$.

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)

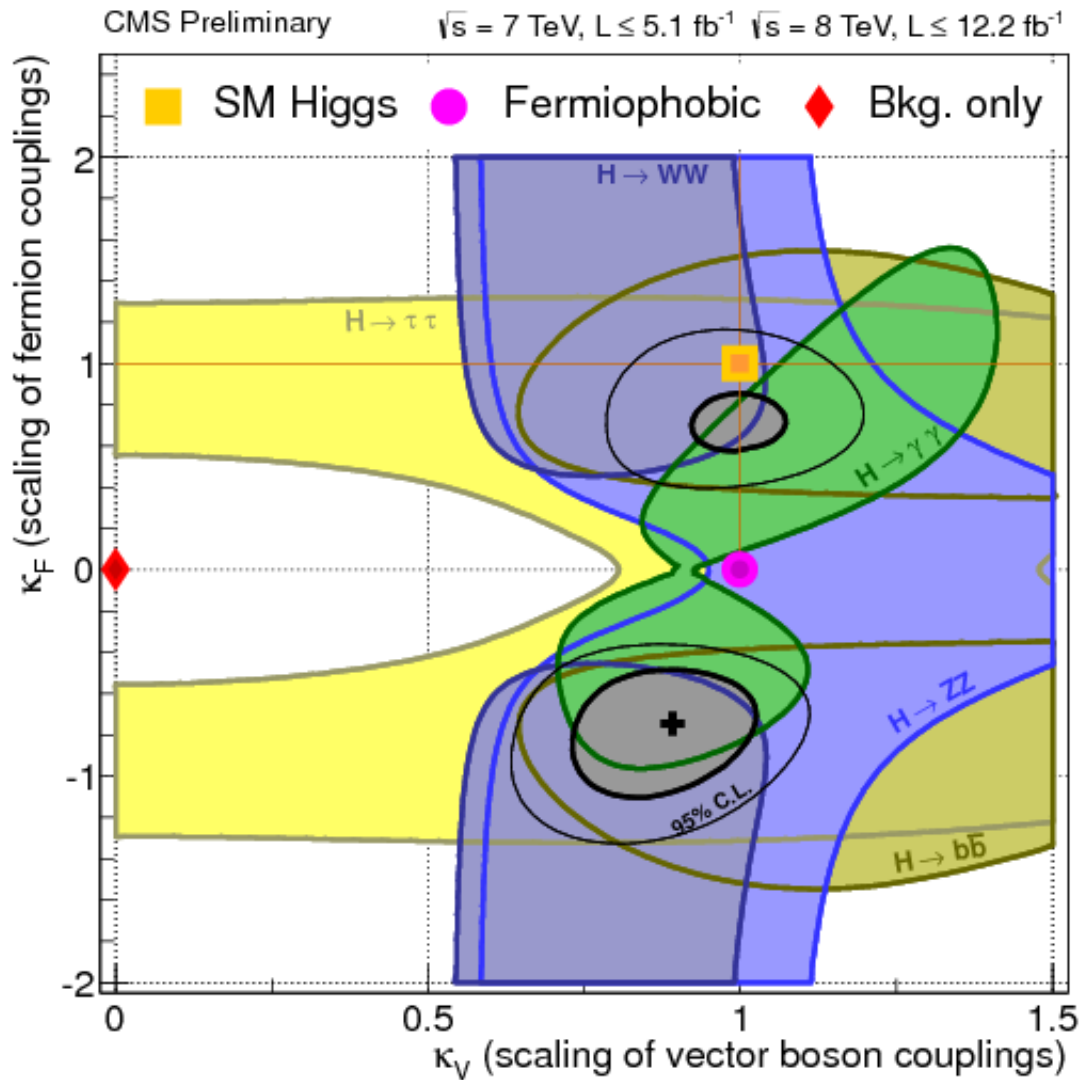This can be interpreted in concrete non-SM Higgs models

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 $\cos^2\theta \equiv \mu = \sigma/\sigma_{\text{SM}}$

$\rightarrow$ Expect to find the orthogonal state somewhere!

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

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

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

$\rightarrow$ Expect to observe invisible decay channel in a missing-energy search!

Going beyond one parameter: $\mathcal{L} \supset \frac{v^2}{4}g^2 V_\mu V^\mu \left(a\frac{2h}{v}\right) - m_i \bar{\psi}_i \psi_i \left(c\frac{h}{v}\right)$

CMS Preliminary $\sqrt{s}$ = 7 TeV, L ≤ 5.1 fb⁻¹ $\sqrt{s}$ = 8 TeV, L ≤ 12.2 fb⁻¹

■ SM Higgs   ● Fermiophobic   ◆ Bkg. only

$a \equiv \kappa_V$
(scaling of vector boson couplings)

$c \equiv \kappa_F$
(scaling of fermion couplings)

CMS December 2012

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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 ξ!

Type-I 2HDM:

$a = \sin(\beta - \alpha)$
$c = \sin(\beta - \alpha) + \cot\beta\cos(\beta - \alpha)$
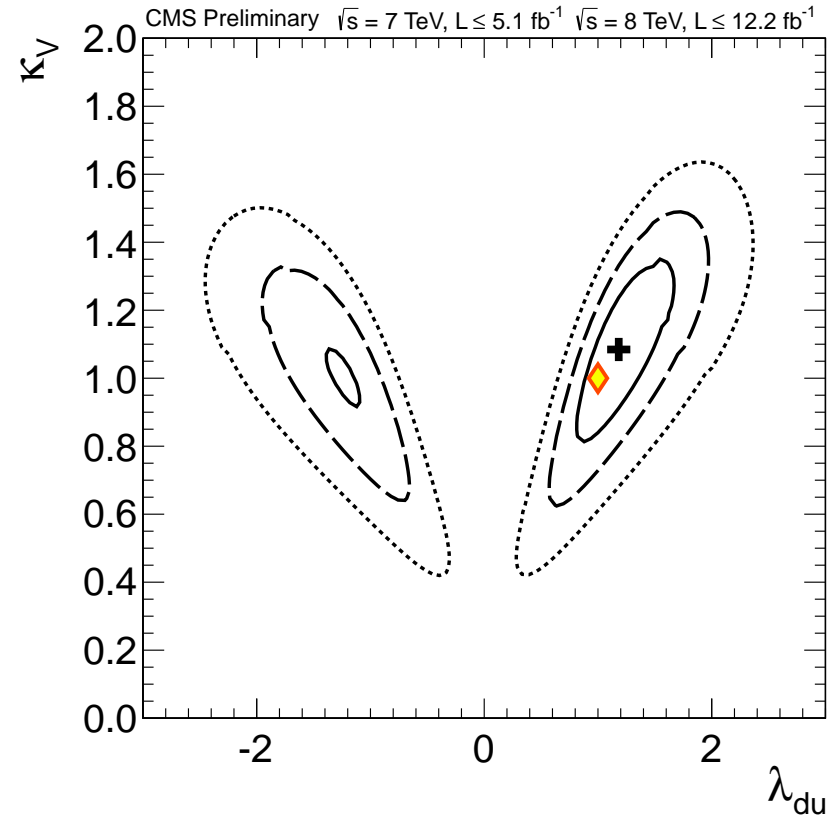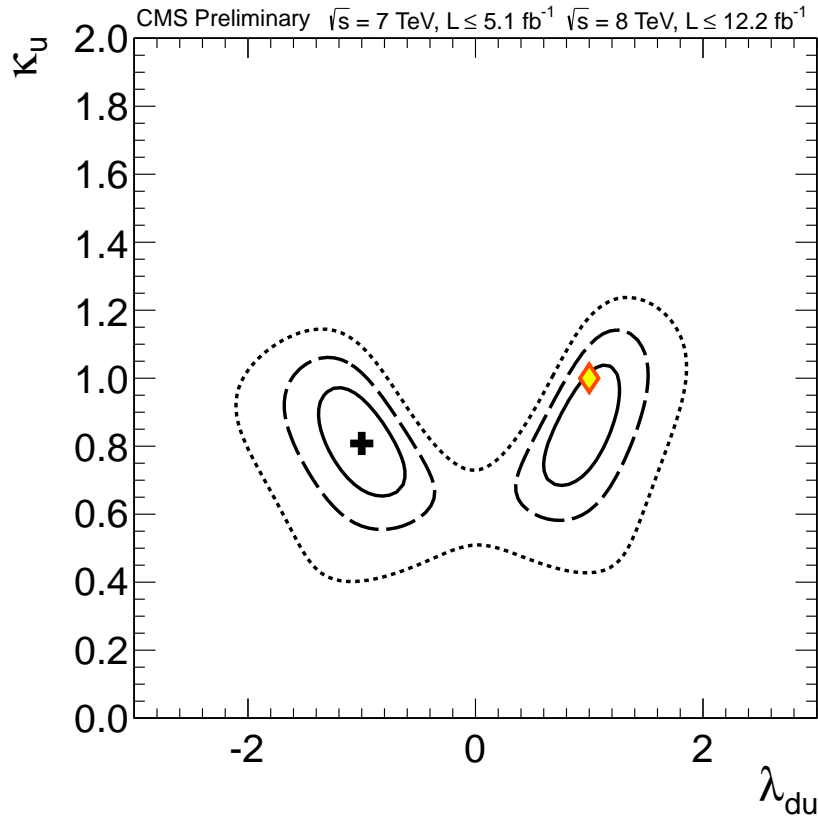
Additional effect in 2HDM-I:
H^+ gives small contribution to $h \to \gamma\gamma$ loop (neglected here).

"Fermiophobic" is $c = 0$, $a = 1$ (not a realistic model; excluded)

"Gaugephobic" is $c = 1$, $a = 0$ (excluded)

Going beyond fermion universality: let $\bar{g}_t \neq \bar{g}_b$

CMS December 2012

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.)

This can be interpreted in concrete non-SM Higgs models

Type-II 2HDM or MSSM:

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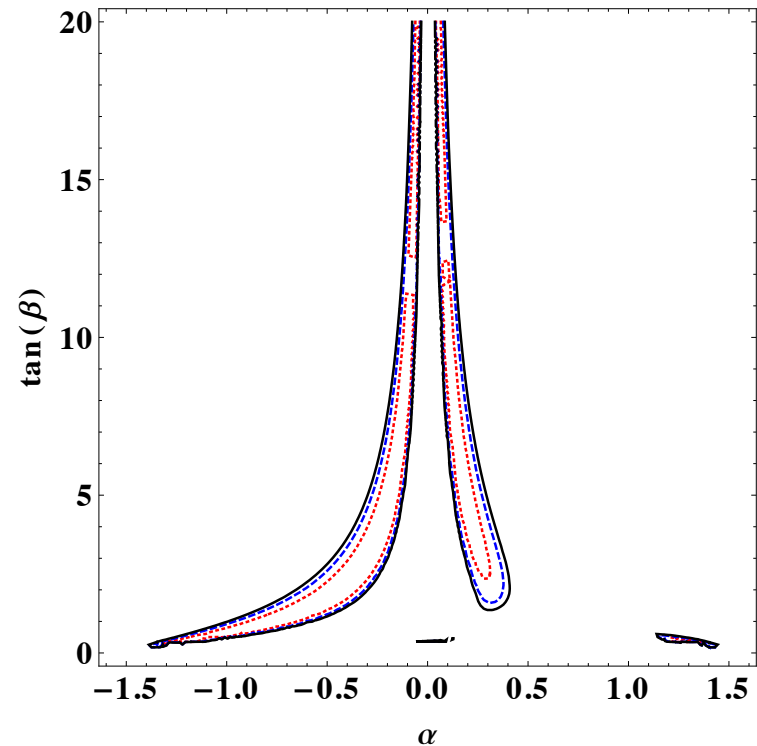$$\bar{g}_b = \bar{g}_\tau = \sin(\beta - \alpha) - \tan\beta\cos(\beta - \alpha)$$

Only 2 underlying free parameters
(mixing angles α and β):
can do a 2-dim fit for α and β!

Warning: theorist-made fit $\rightarrow$

Additional effect in 2HDM-II:
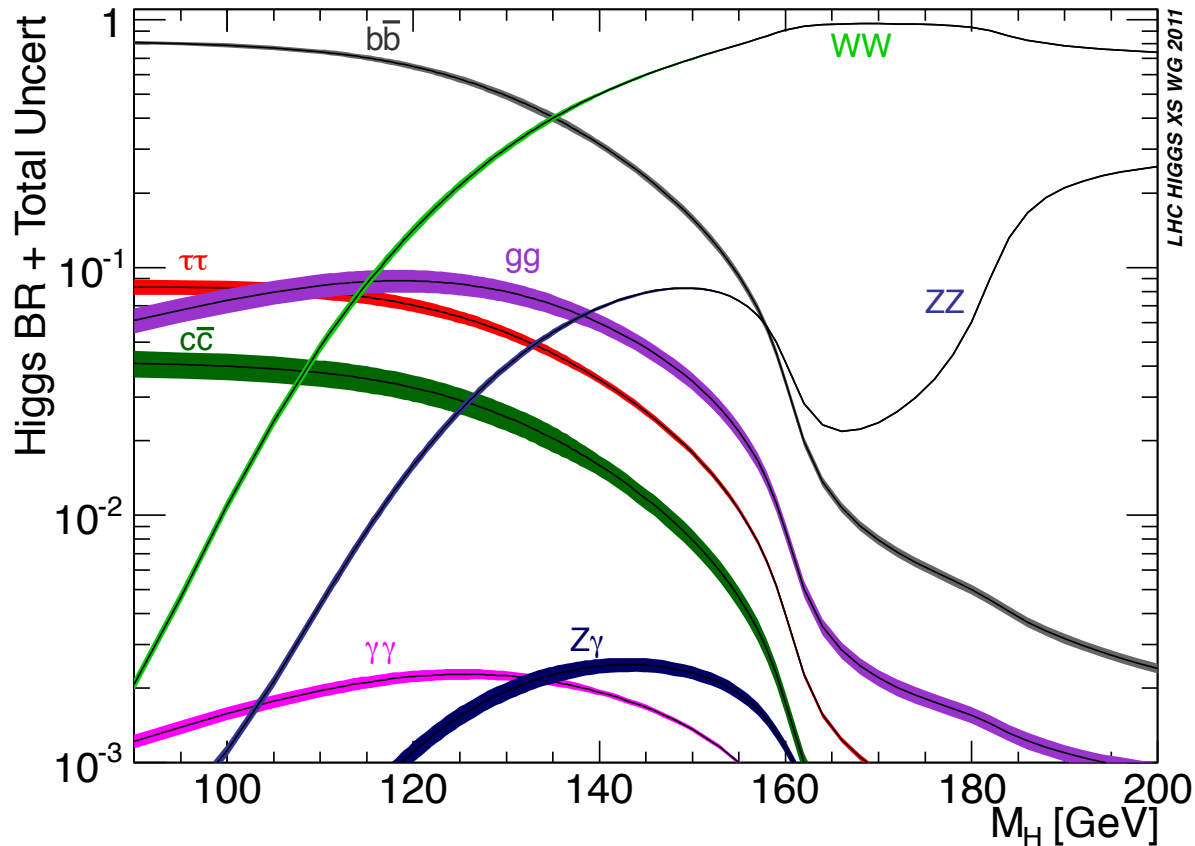H^+ gives small contribution to $h \rightarrow$
$\gamma\gamma$ loop (neglected here).
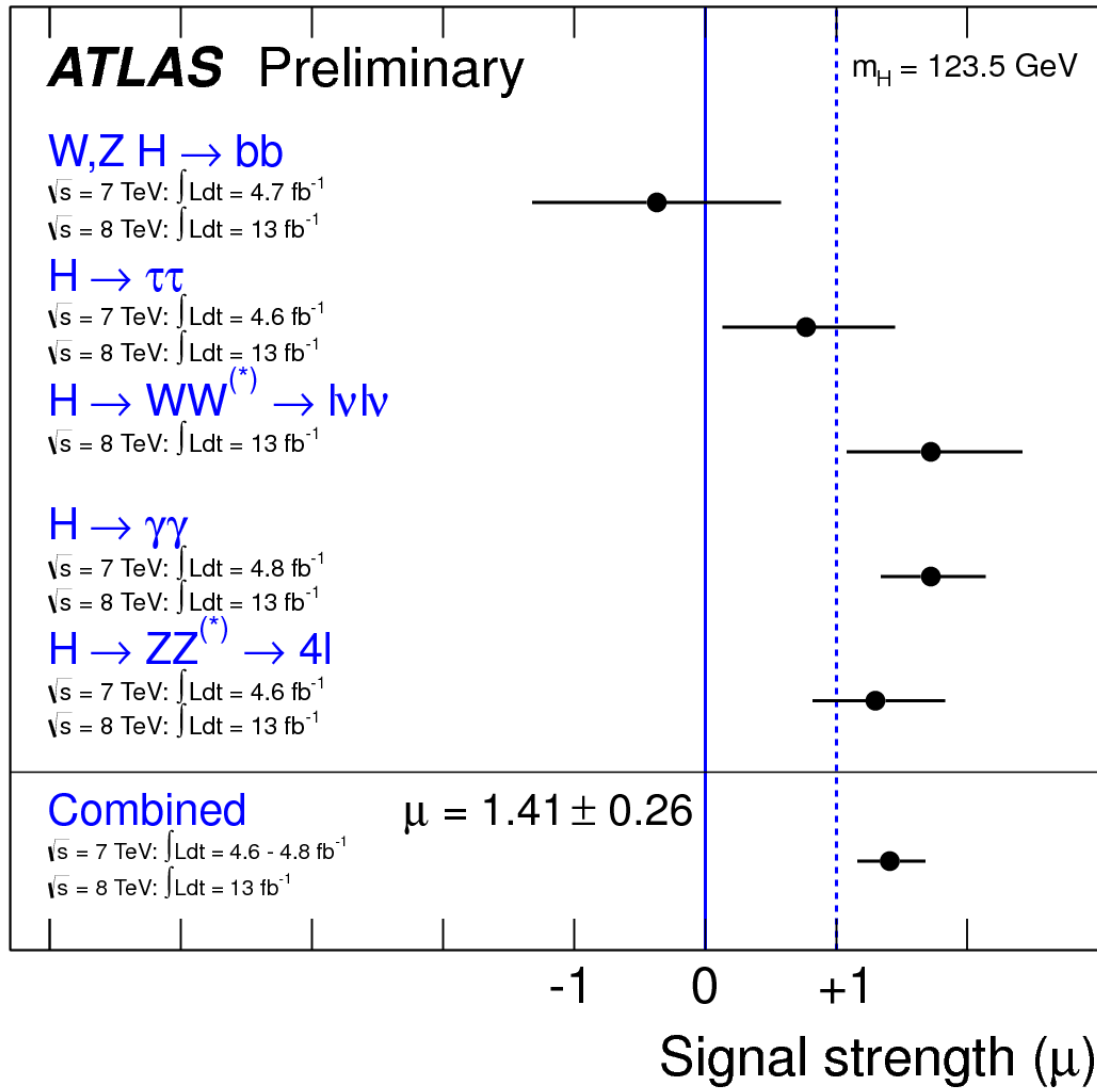
Chen and Dawson, 1301.0309

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 $\bar{g}_b/\bar{g}_W$.

A note on Higgs mass dependence

ATLAS Preliminary — m_H = 123.5 GeV

W,Z H → bb
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.7 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13 fb^{-1}

H → ττ
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13 fb^{-1}

H → WW$^{(*)}$ → lνlν
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13 fb^{-1}

H → γγ
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13 fb^{-1}

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

Combined $\mu = 1.41 \pm 0.26$
$\sqrt{s}$ = 7 TeV: ∫Ldt = 4.6 - 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: ∫Ldt = 13 fb^{-1}

-1   0   +1

Signal strength (μ)

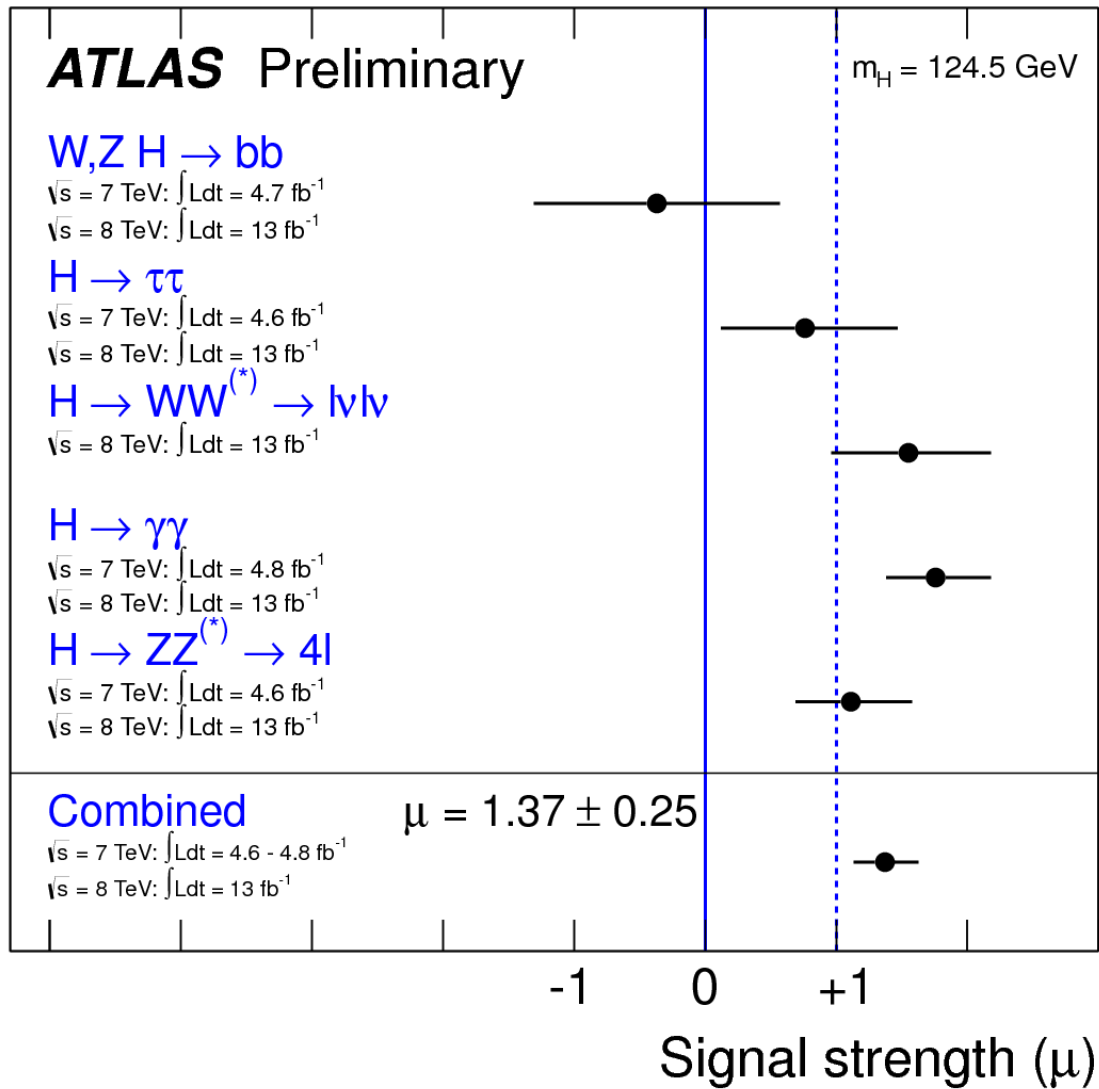ATLAS Higgs combination December 2012

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A note on Higgs mass dependence

ATLAS Preliminary

$m_H = 124.5$ GeV

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

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

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

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

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

Combined $\mu = 1.37 \pm 0.25$
$\sqrt{s} = 7$ TeV: $\int$Ldt = 4.6 - 4.8 fb^{-1}
$\sqrt{s} = 8$ TeV: $\int$Ldt = 13 fb^{-1}

-1   0   +1

Signal strength (μ)

ATLAS Higgs combination December 2012

A note on Higgs mass dependence

ATLAS Preliminary $m_H = 125.5$ GeV

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

H → γγ
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$\sqrt{s} = 8$ TeV: $\int$Ldt = 13 fb^{-1}

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

Combined $\mu = 1.33 \pm 0.24$
$\sqrt{s} = 7$ TeV: $\int$Ldt = 4.6 - 4.8 fb^{-1}
$\sqrt{s} = 8$ TeV: $\int$Ldt = 13 fb^{-1}

-1   0   +1

Signal strength (μ)

ATLAS Higgs combination December 2012

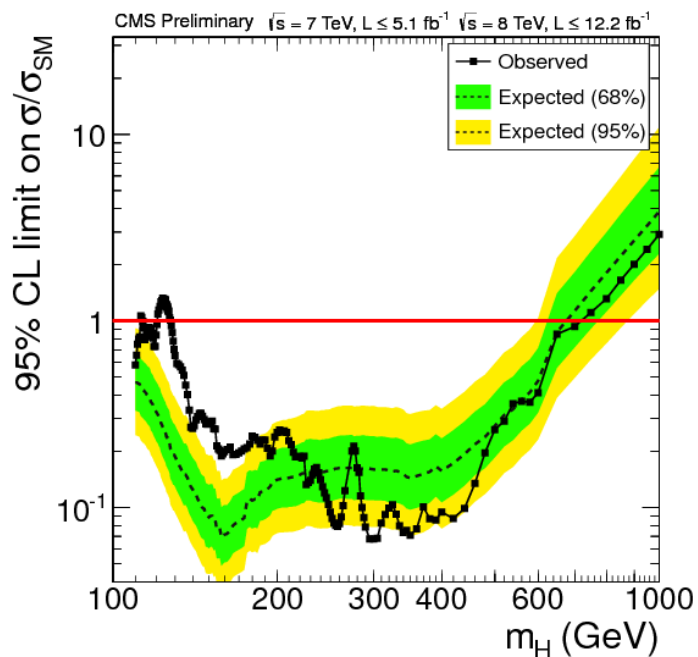Heather Logan (Carleton U.)   Higgs boson   UdeM/McGill Feb 2013

A note on Higgs mass dependence
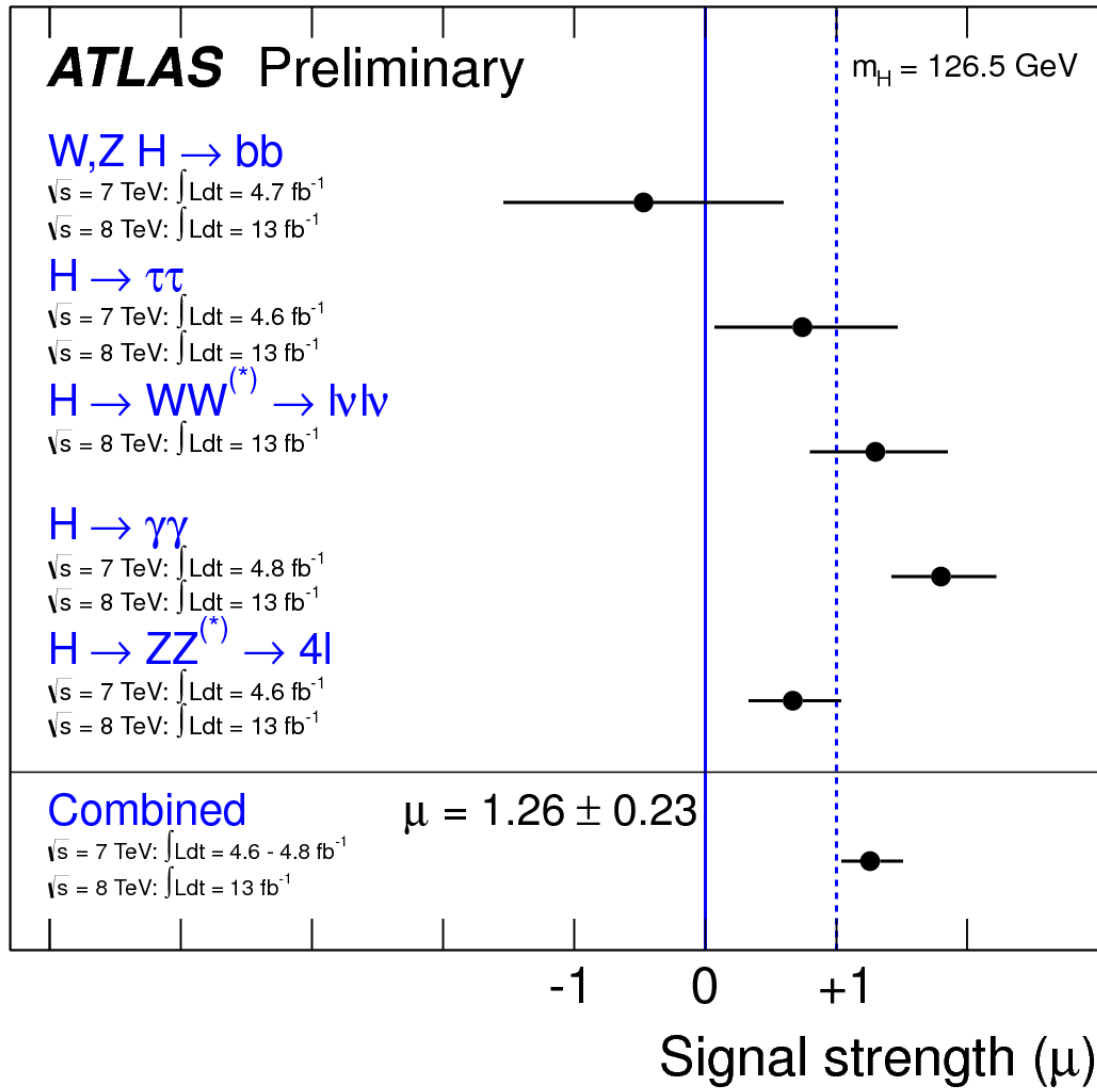
Synergy between couplings of h and searches for additional states

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.

CMS Preliminary $\sqrt{s} = 7$ TeV, L ≤ 5.1 fb^{-1} $\sqrt{s} = 8$ TeV, L ≤ 12.2 fb^{-1}

- Observed
- Expected (68%)
- Expected (95%)

95% CL limit on σ/σ_{SM}

m_H (GeV)

SM Higgs mixed with a gauge-singlet scalar:

$$h = \phi \cos\theta - s \sin\theta \qquad H = \phi \sin\theta + s \cos\theta$$

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

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

Dedicated searches for H: probe $\sigma/\sigma_{\mathsf{SM}}$ as function of M_H, Γ_H.

Two Higgs doublet models:

$$h = -\sin\alpha\,\phi_1 + \cos\alpha\,\phi_2 \qquad H = \cos\alpha\,\phi_1 + \sin\alpha\,\phi_2$$

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: $\bar{g}_t = \cos(\beta - \alpha) - \cot\beta\sin(\beta - \alpha)$
$$\bar{g}_b = \cos(\beta - \alpha) + \tan\beta\sin(\beta - \alpha)$$

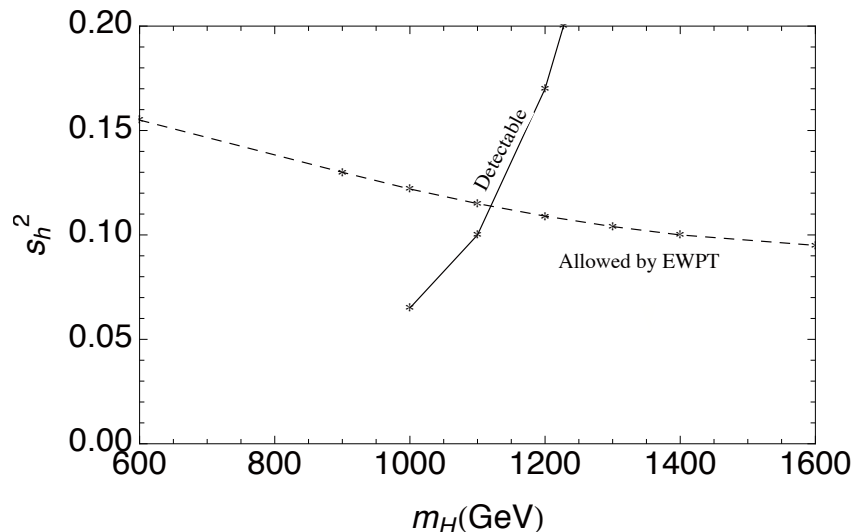Constrain couplings of $h \longrightarrow$ predict production and decays of H

Mass of H is constrained by same physics as SM Higgs mass.

$WW \to WW$ scattering:

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

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

Electroweak fit:

m_H(GeV)

SM + singlet:
$$S = a^2 S_{\text{SM}}(M_h) + (1 - a^2) S_{\text{SM}}(M_H)$$
Similar for T parameter.
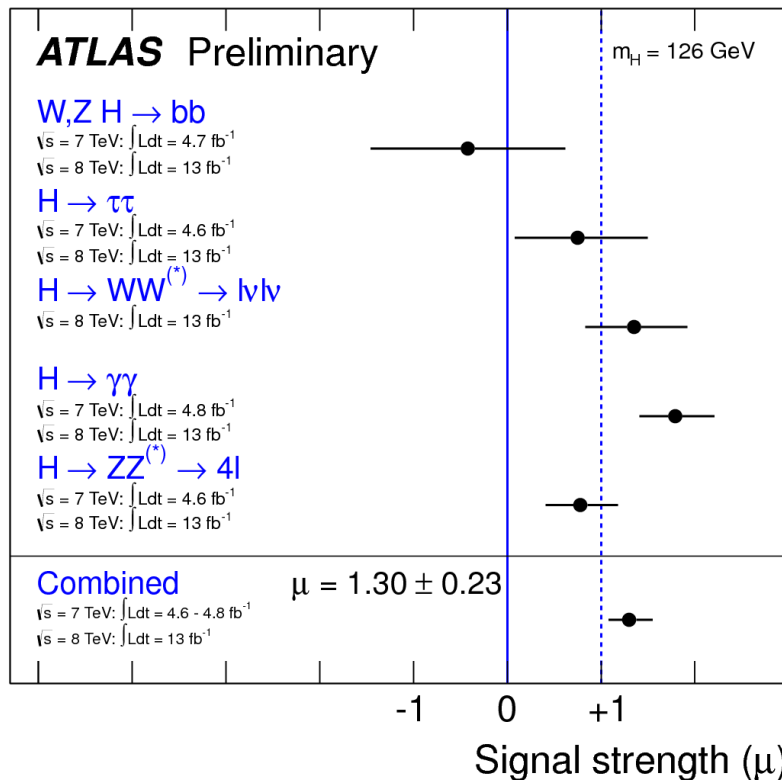Depends on $\log(M_H)$.

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

Can evade limit with new physics.

Gupta, Rzehak, Wells, 1206.3560

EXPERIMENTAL PROSPECTS

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 fb^{-1} collected per expt. at 7 + 8 TeV up to now.

Expect 300 fb^{-1}/expt. at 13-14 TeV

- Also, larger cross sections

Expected precisions:
$\sim 30\%$ for $h \to WW$, VBF $h \to \gamma\gamma$
$\sim 20\%$ for VBF $h \to \tau\tau$
$\sim 10\%$ for $h \to ZZ$, $h \to \gamma\gamma$

High-luminosity LHC upgrade
> 2022, $\to 3000$ fb^{-1}/expt.
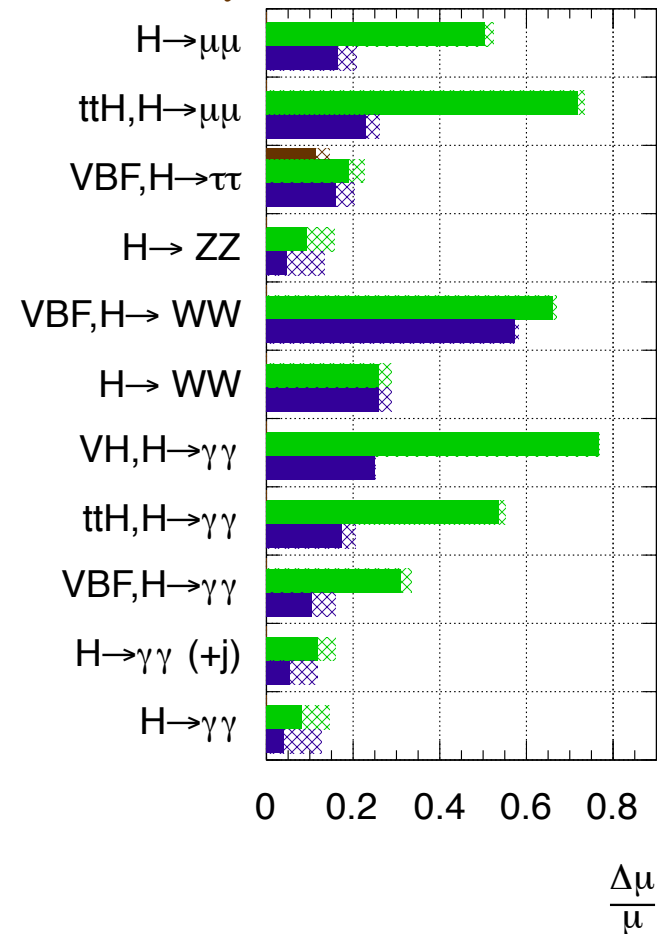
Add tth channels $\sim 20\%$, $h \to \mu\mu$
Improve VBF, Vh $h \to \gamma\gamma$ 15-30%

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

ATL-PHYS-PUB-2012-004 (European Strategy study)

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

H→μμ
ttH,H→μμ
VBF,H→ττ
H→ZZ
VBF,H→WW
H→WW
VH,H→γγ
ttH,H→γγ
VBF,H→γγ
H→γγ (+j)
H→γγ

0   0.2   0.4   0.6   0.8

$\frac{\Delta\mu}{\mu}$

Extracting individual Higgs couplings:
- need to do a fit of multiple channels
- LHC: must make theory assumption to constrain total width

$g(hAA)/g(hAA)|_{SM} - 1$ LHC

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

For higher precision: e^+e^- Higgs factory

ILC: 250 fb^{-1} at 250 GeV: peak of $e^+e^- \to Zh$ 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%)
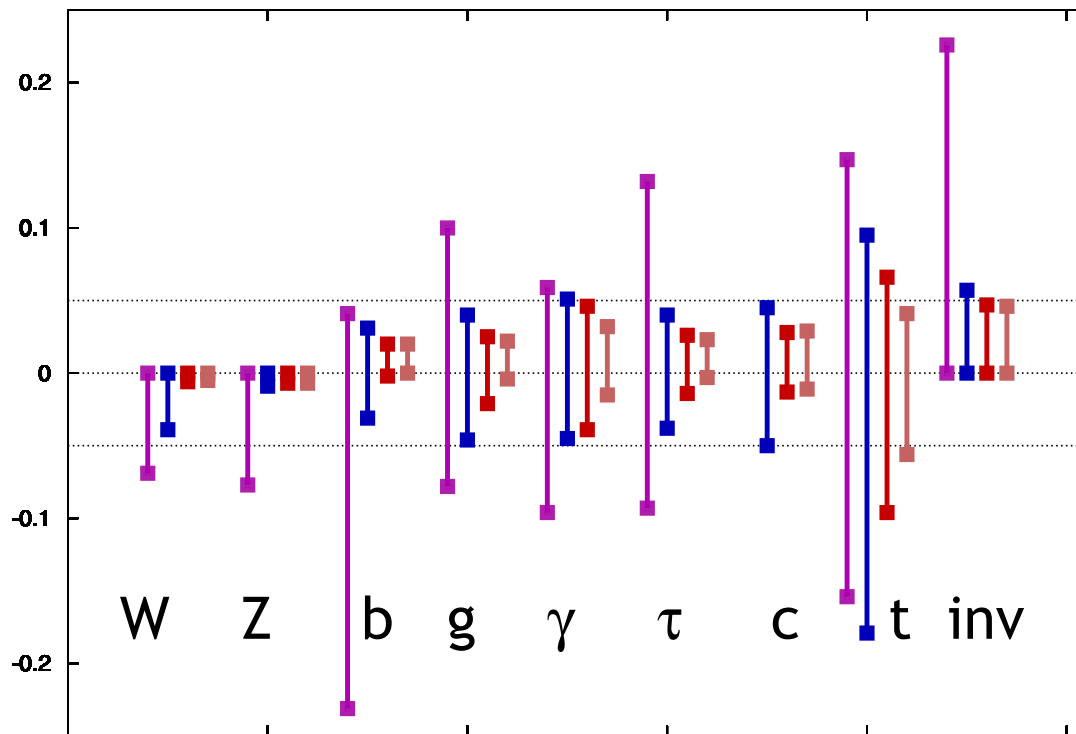
ILC: 500 fb^{-1} at 500 GeV:
- WBF $e^+e^- \to \nu\bar{\nu}h$: Γ_{tot} from combining with BR(WW)
- $e^+e^- \to tth$ for top quark Yukawa coupling
- $e^+e^- \to Zhh$ for Higgs self-coupling ($\sim 27\%$ with 2000 fb^{-1})

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

For higher precision: e^+e^- Higgs factory

$g(hAA)/g(hAA)|_{SM}$-1   LHC/ILC1/ILC/ILCTeV

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

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?

BACKUP SLIDES

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 α and β),

plus small contribution of H^+ to $h \to \gamma\gamma$ 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. $\rightarrow$ correlations

Coupling extraction strategy

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

$$\mathsf{Rate}_{ij} = \sigma_i \, \mathsf{BR}_j = \sigma_i \frac{\Gamma_j}{\Gamma_{\mathsf{tot}}}$$

Coupling dependence (at leading order):

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$$\Gamma_j = \bar{g}_j^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$

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

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}. $\hspace{2em} \Gamma_{\text{tot}} \geq \Gamma(h \to WW, ZZ)$

Theory assumption that $\bar{g}_W \leq 1$ and $\bar{g}_Z \leq 1$: $\hspace{3em} \Leftarrow!$

    (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}. $\hspace{2em} \Gamma_{\text{tot}} = \Gamma(h \to WW)/\text{BR}(h \to WW)$

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)

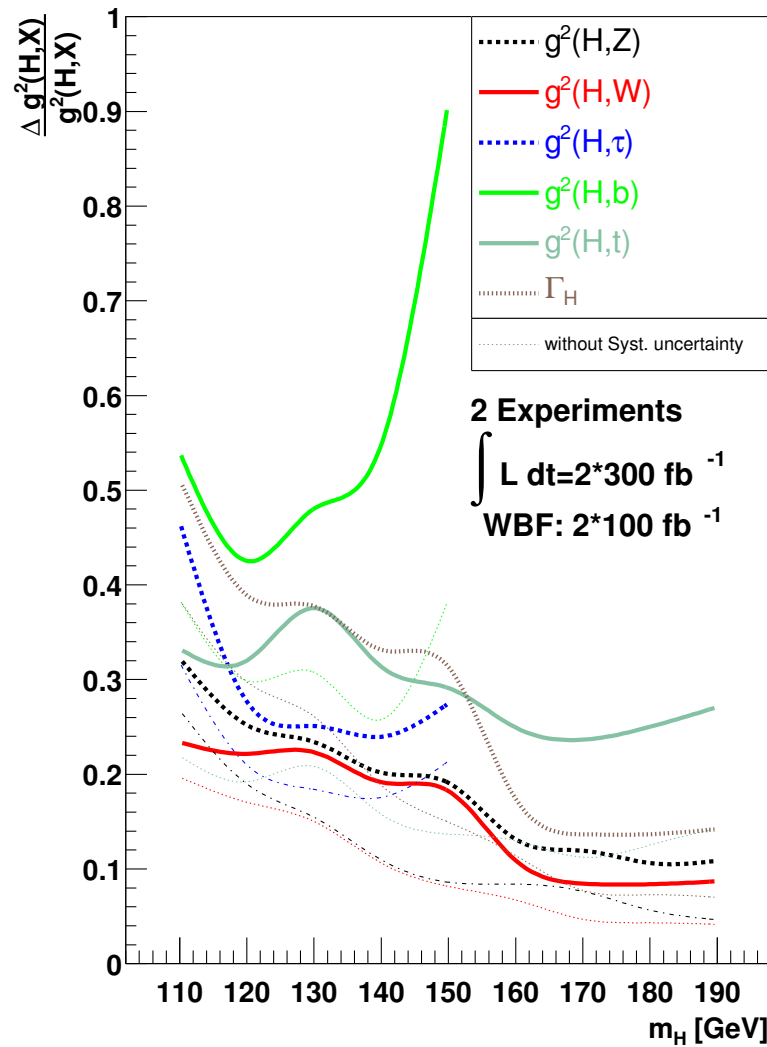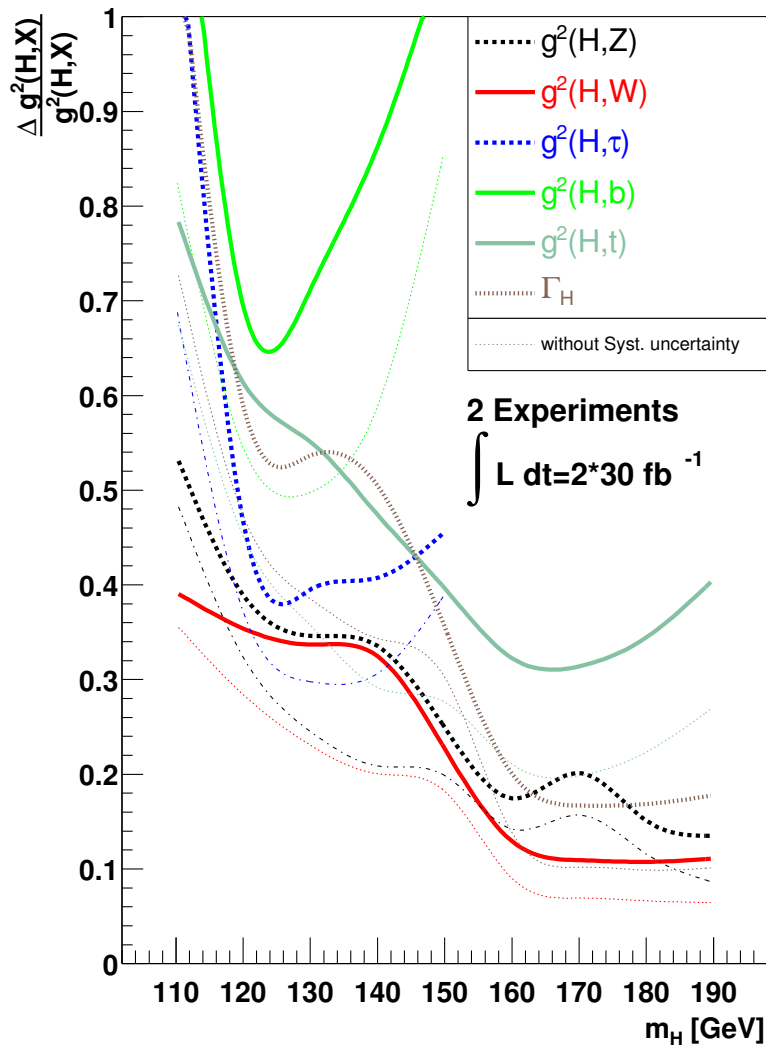WH, $H \to \gamma\gamma$ ($M_h \leq$ 120 GeV)

ZH, $H \to \gamma\gamma$ ($M_h \leq$ 120 GeV)

$t\bar{t}H$, $H \to b\bar{b}$ $\Leftarrow$!!

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 $gg \to H \to WW$ Inclusive $H \to \gamma\gamma$

VBF $qqH \to qqWW$ VBF $qqH \to qq\gamma\gamma$

$t\bar{t}H$, $H \to WW$ $t\bar{t}H$, $H \to \gamma\gamma$ $(M_h \leq 120$ GeV$)$

                                WH, $H \to \gamma\gamma$ $(M_h \leq 120$ GeV$)$

GF $gg \to H \to ZZ$ ZH, $H \to \gamma\gamma$ $(M_h \leq 120$ GeV$)$

VBF $qqH \to qqZZ$

                                $t\bar{t}H$, $H \to b\bar{b}$ $\times 50\%$ vs. 2004 study

VBF $qqH \to qq\tau\tau$ 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)

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

$$\Delta \bar{g}_b^2 \sim 65\% \to 45\% \qquad \Delta \bar{g}_\tau^2 \sim 40\% \to 25\% \qquad \bar{g}_W = \bar{g}_Z \le 1$$
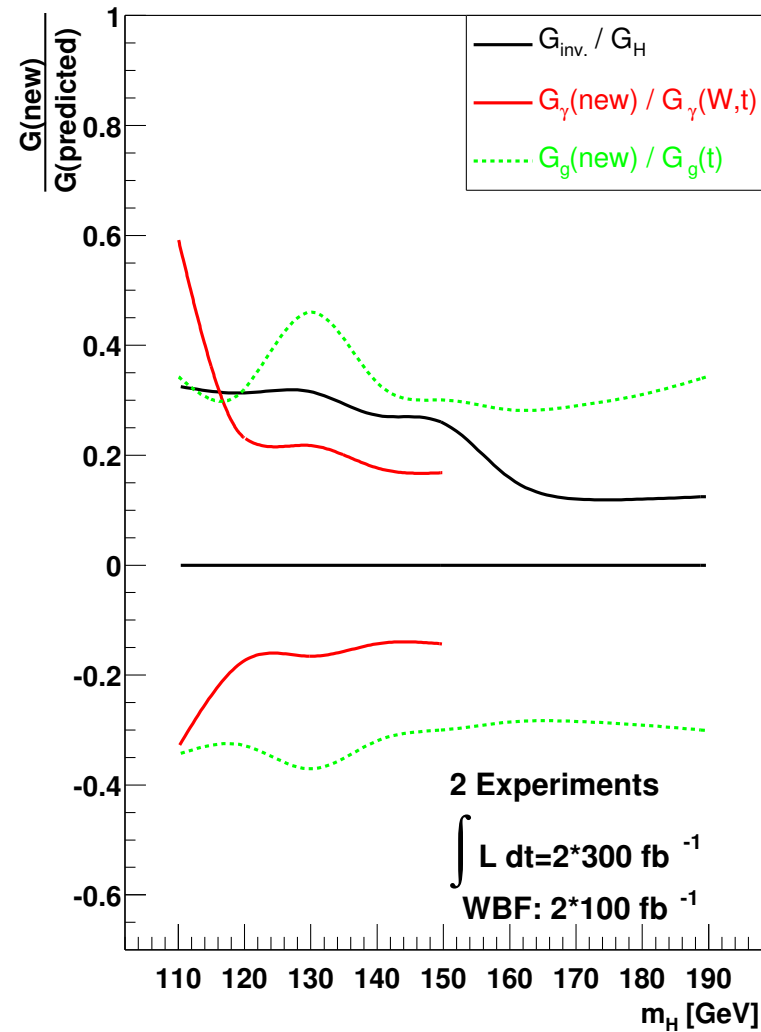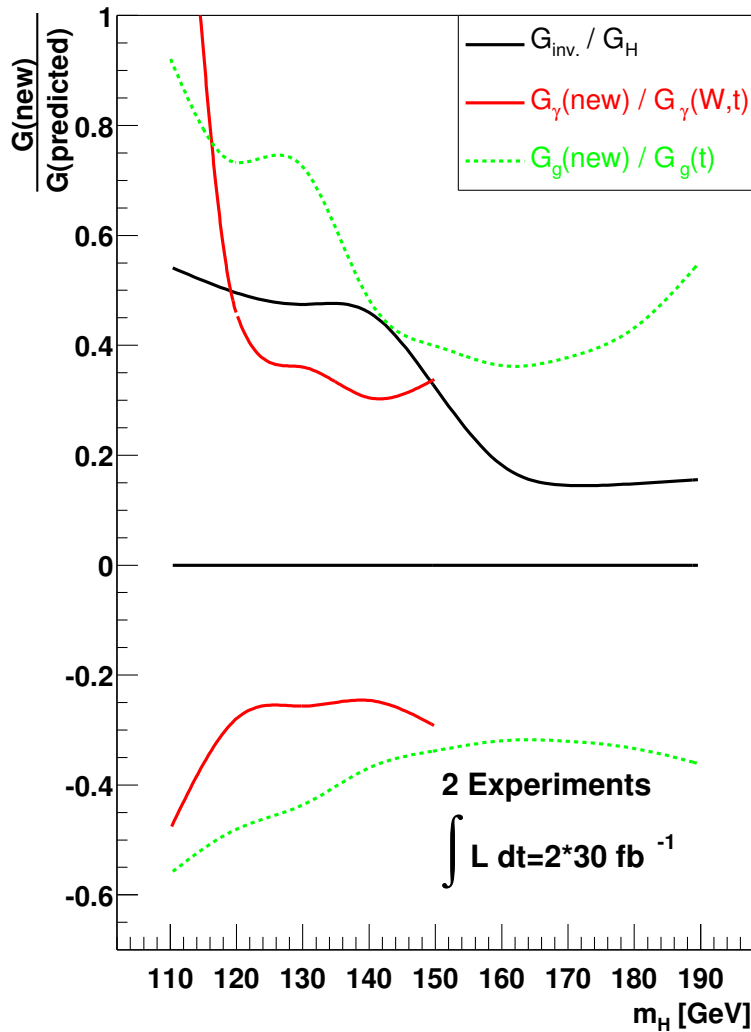
$$\Gamma_{unobs} \leq 50\% \rightarrow 35\% \text{ of } \Gamma_{tot,fit} \qquad \text{for 125 GeV Higgs}$$

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

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

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

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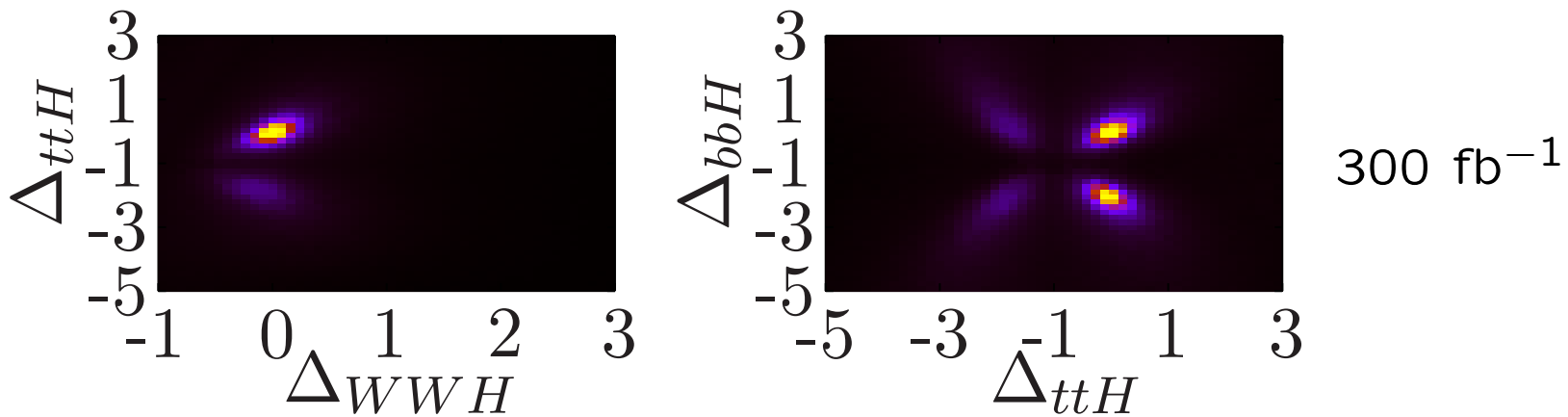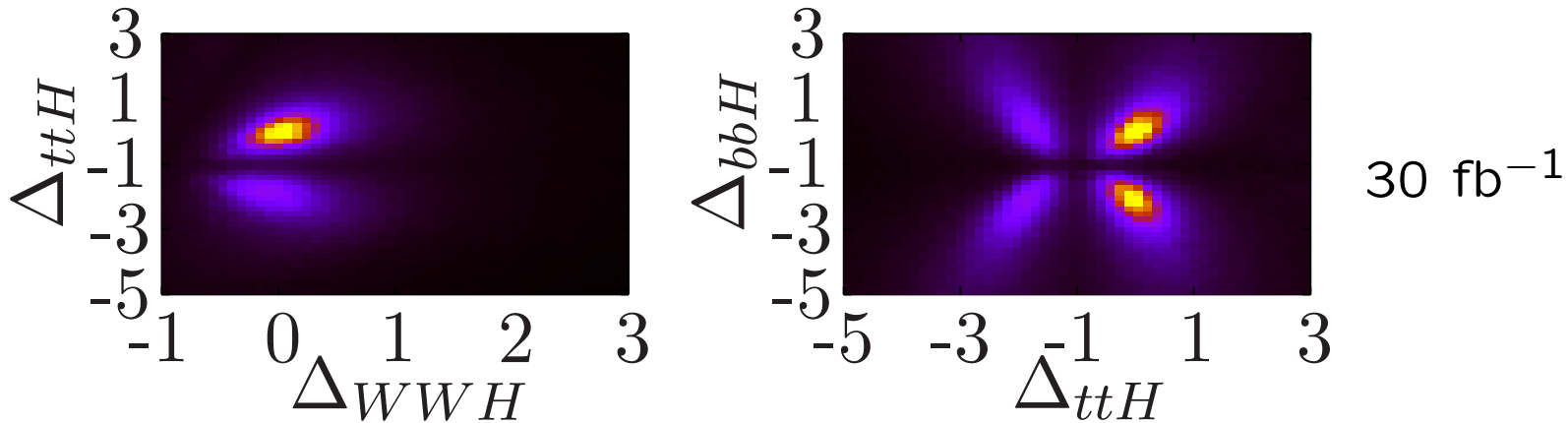
Lafaye, Plehn, Rauch, D. Zerwas, & Dührssen, JHEP 0908, 009 (2009)

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 ~ 125 GeV: crucial for constraining Γ_{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 $b\bar{b} \to h$.

- $\sigma(A \to h) * \mathrm{BR}(H \to X) \propto \Gamma_A \Gamma_X / \Gamma_{\mathrm{tot}}$ 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 <u>fixed</u> by the mass-generation mechanism $\rightarrow$ variation with M_h is due to kinematics.
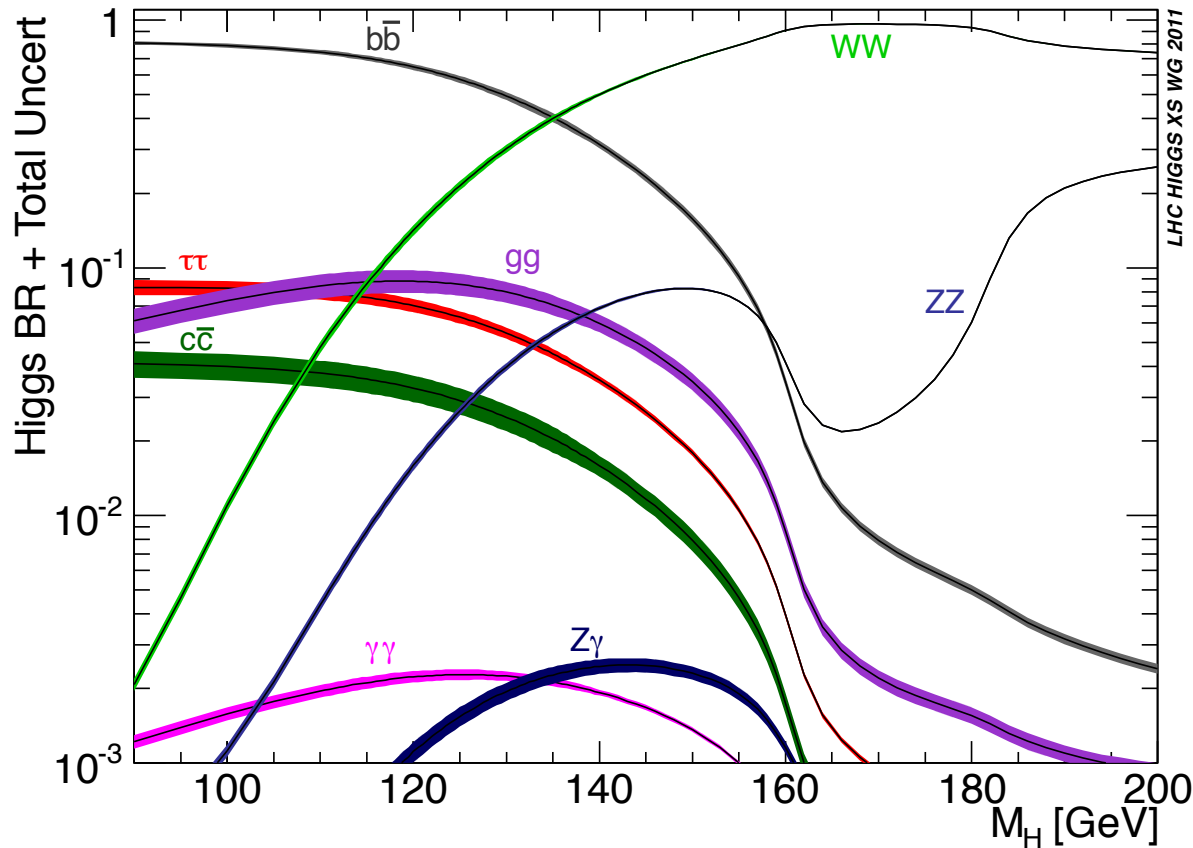
1 GeV uncertainty in M_h $\Rightarrow$ 5% uncertainty in $\bar{g}_b/\bar{g}_W$.
100 MeV uncertainty in M_h $\Rightarrow$ 0.5% uncertainty in $\bar{g}_b/\bar{g}_W$.
M_h could be included as a correlated fit parameter.

Conclusions

LHC data will let us measure Higgs couplings to
W, Z, t, b, 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?
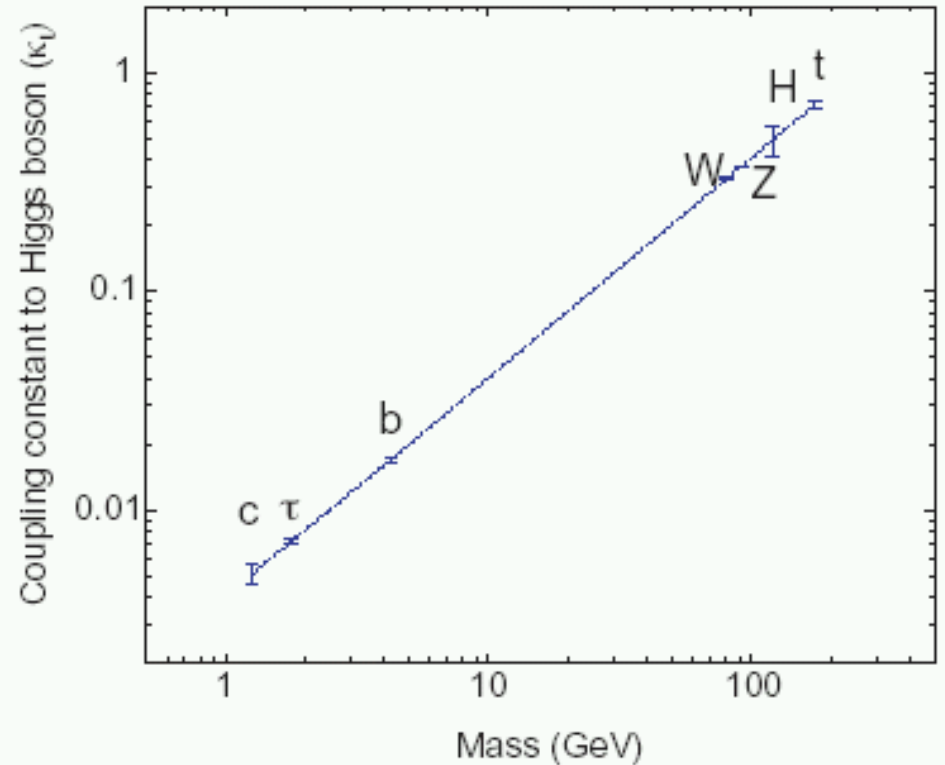
The Carleton Theory Group wants YOU!

Openings for up to 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

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