# Characterizing the Higgs at the LHC

Heather Logan
*Carleton University*

Physics colloquium
Carleton University, May 29, 2012

## Outline

- Introduction: why a Higgs?

- Why measure Higgs couplings?

- Coupling extraction from LHC measurements*

- What we learn: couplings in specific models

- Conclusions

*I will not talk about measuring spin, CP, etc.

The Standard Model is extremely successful so far.

Can't we get by with just the degrees of freedom that we've observed?

- 3 generations of quarks; CKM matrix for flavor physics
- 3 generations of charged leptons
- Neutrinos with mass (might need something new there)
- gluons from SU(3) strong interaction
- photon plus massive $W^{\pm}$ and $Z$ from SU(2) $\times$ U(1)

(Electroweak symmetry is broken, but do we really have to worry about how?)

- (Dark matter?)
- (Quantum gravity?)

The Standard Model is extremely successful so far.

Can't we get by with just the degrees of freedom that we've observed?

- 3 generations of quarks; CKM matrix for flavor physics
- 3 generations of charged leptons
- Neutrinos with mass (might need something new there)
- gluons from SU(3) strong interaction
- photon plus massive $W^{\pm}$ and $Z$ from SU(2) $\times$ U(1)

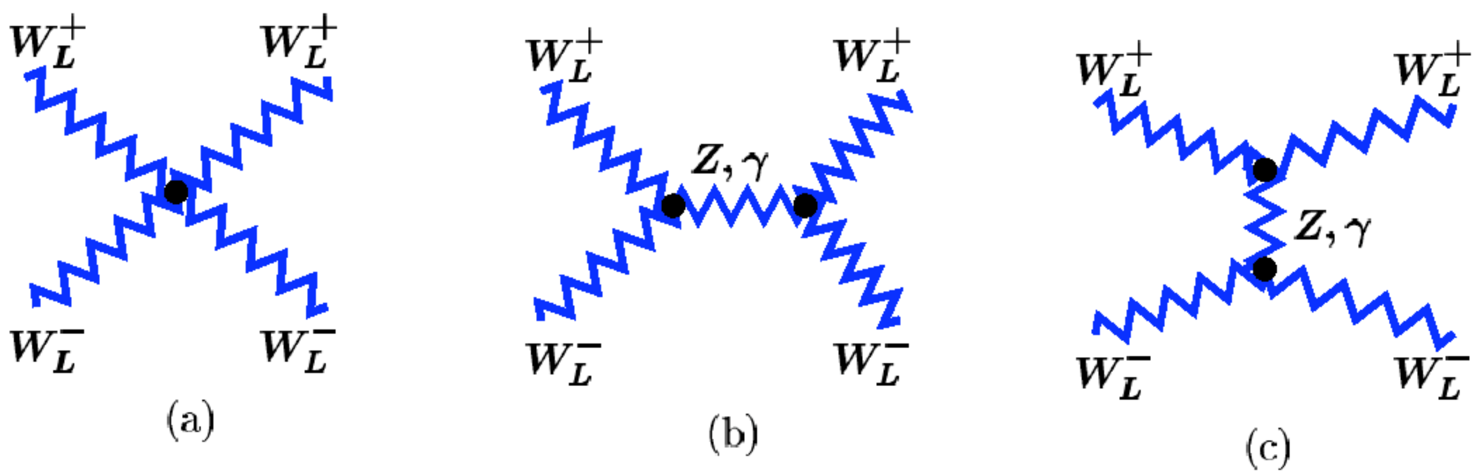
(Electroweak symmetry is broken, but do we really have to worry about how?)

- (Dark matter?)
- (Quantum gravity?)

The answer is NO:
the SM without a Higgs is intrinsically incomplete.

## Scattering of longitudinally-polarized $W$s exposes need for a Higgs*

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




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

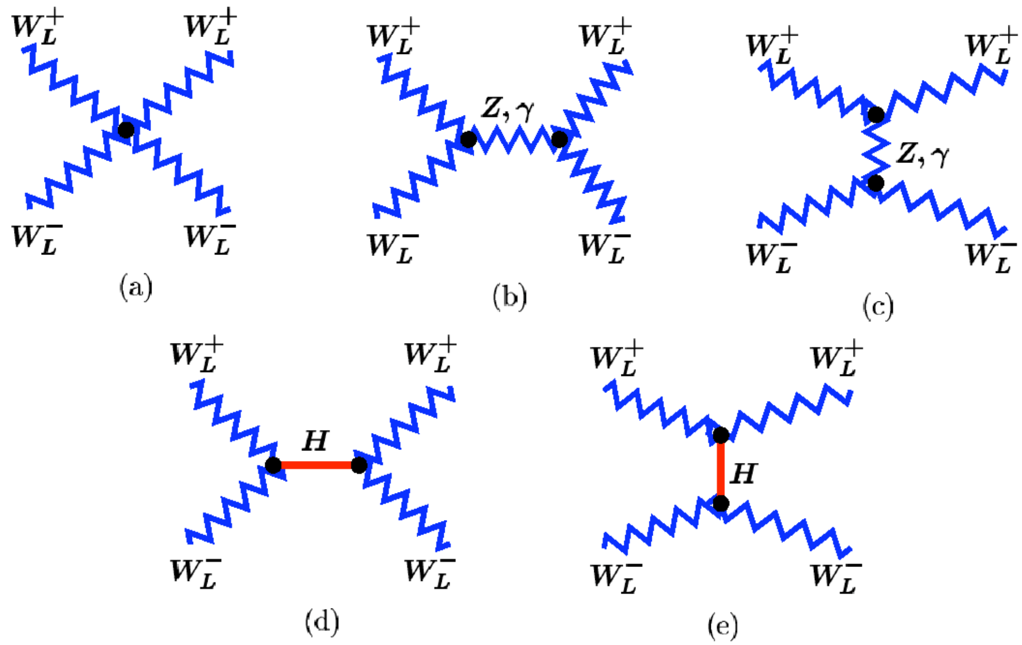
$$\epsilon_L^\mu(k) = \frac{k^\mu}{m_w} + \mathcal{O}\left(\frac{m_w}{E}\right)$$

Graphics from R.S. Chivukula, LHC4ILC 2007

*or something to play its role

Scattering of longitudinally-polarized $W$s exposes need for a Higgs*

# SU(2) x U(1) @ E$^2$




| Graphs | $g^2 \frac{E^2}{m_w^2}$ |
|---|---|
| (a) | $+2 - 6\cos\theta$ |
| (b) | $-\cos\theta$ |
| (c) | $-\frac{3}{2} + \frac{15}{2}\cos\theta$ |
| (d + e) | $-\frac{1}{2} - \frac{1}{2}\cos\theta$ |
| **Sum** including (d+e) | **0** |

- ▶ $\mathcal{O}(E^0) \Rightarrow$ 4d $m_H$ bound: $m_H < \sqrt{16\pi/3}\,v \simeq 1.0\,\text{TeV}$
- ▶ If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{8\pi}v \simeq 1.2\,\text{TeV}$

Graphics from R.S. Chivukula, LHC4ILC 2007

*or something to play its role

## 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

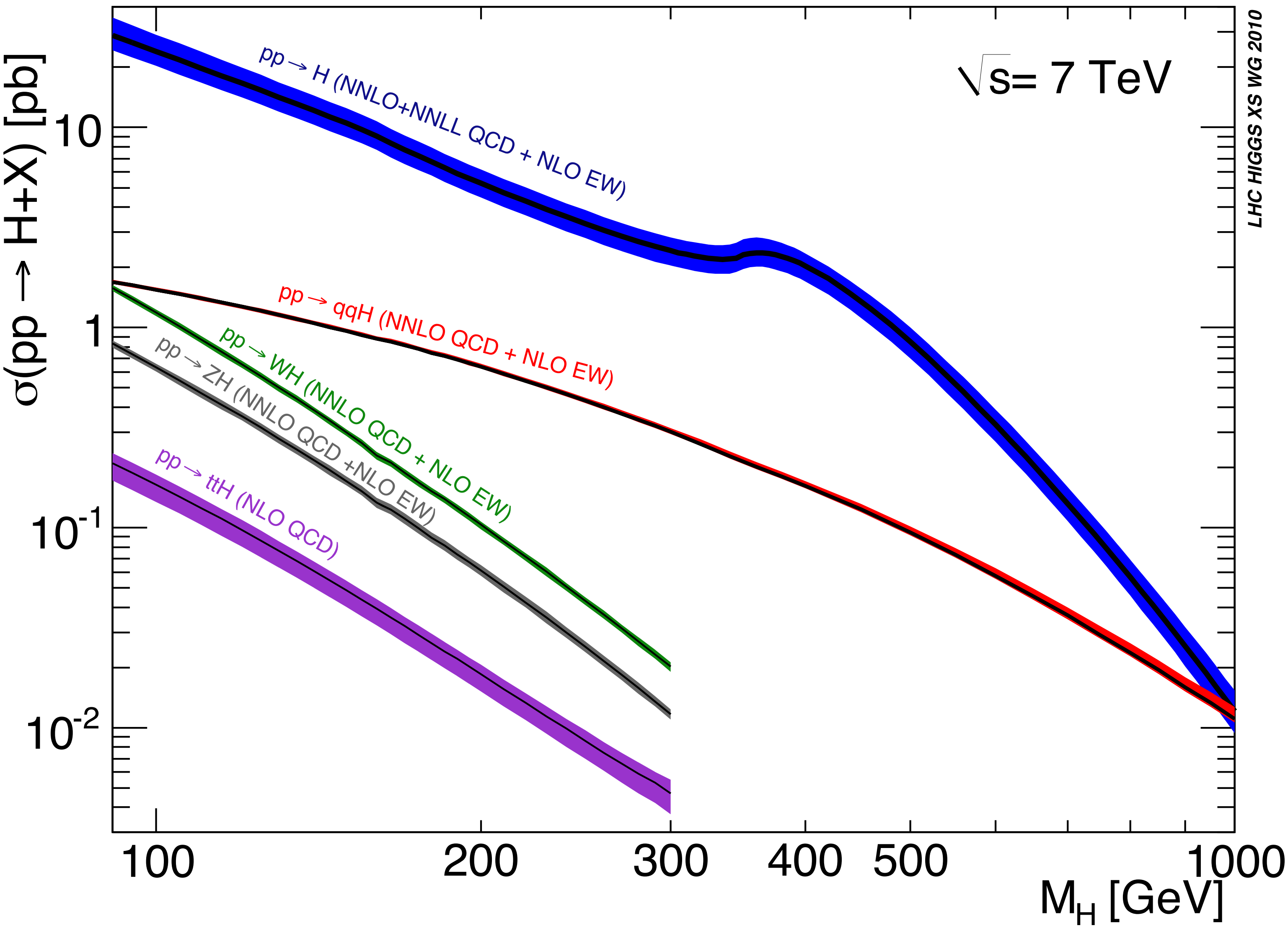
$$\mathcal{L} = |\mathcal{D}_\mu H|^2 \;\rightarrow\; (g^2/4)(h+v)^2 W^+ W^- + (g_Z^2/8)(h+v)^2 ZZ$$
$$M_W^2 = g^2 v^2/4 \qquad hWW:\; i(g^2 v/2) g^{\mu\nu}$$
$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ:\; i(g_Z^2 v/2) g^{\mu\nu}$$

Fermions:

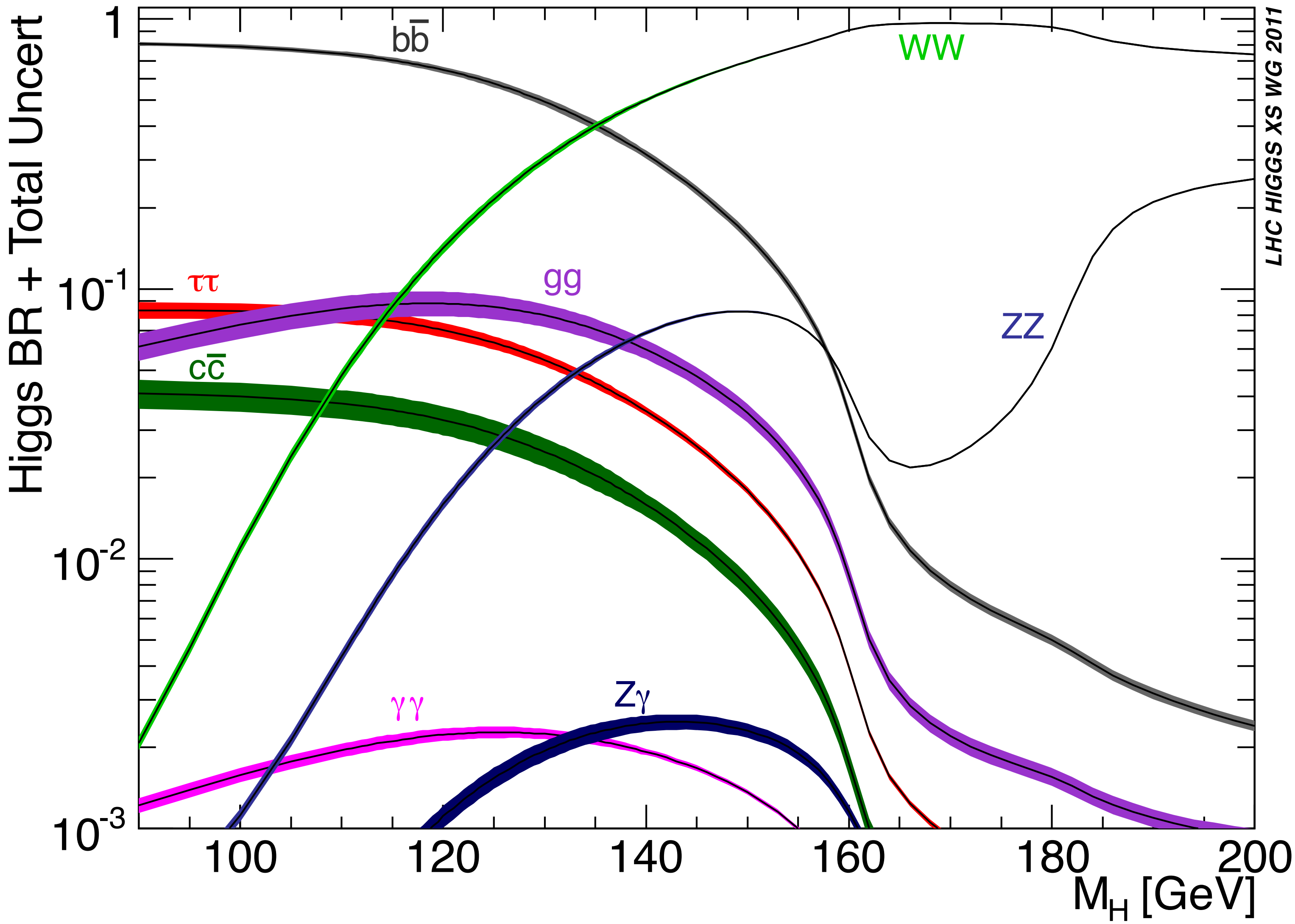
$$\mathcal{L} = -y_f \bar{f}_R H^\dagger Q_L + \cdots \;\rightarrow\; -(y_f/\sqrt{2})(h+v)\bar{f}_R f_L + \text{h.c.}$$
$$m_f = y_f v/\sqrt{2} \qquad h\bar{f}f:\; i m_f/v$$

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

Predict SM Higgs production cross sections

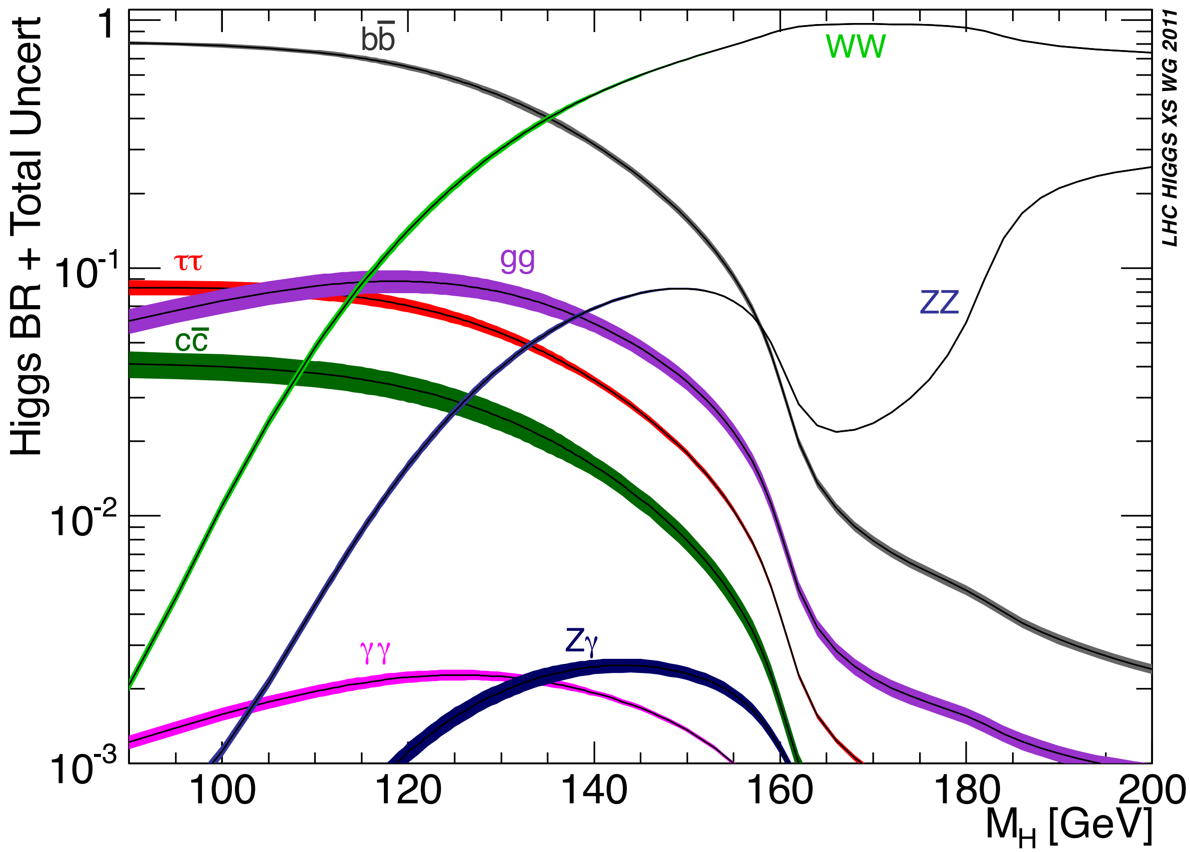


Predict SM Higgs decay branching ratios



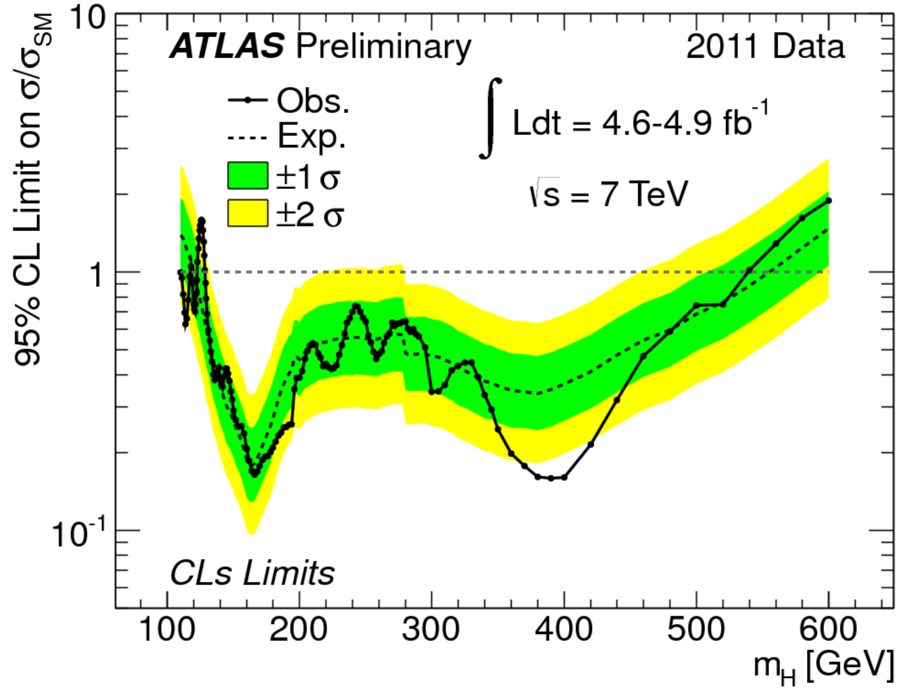
## A note on Higgs mass dependence

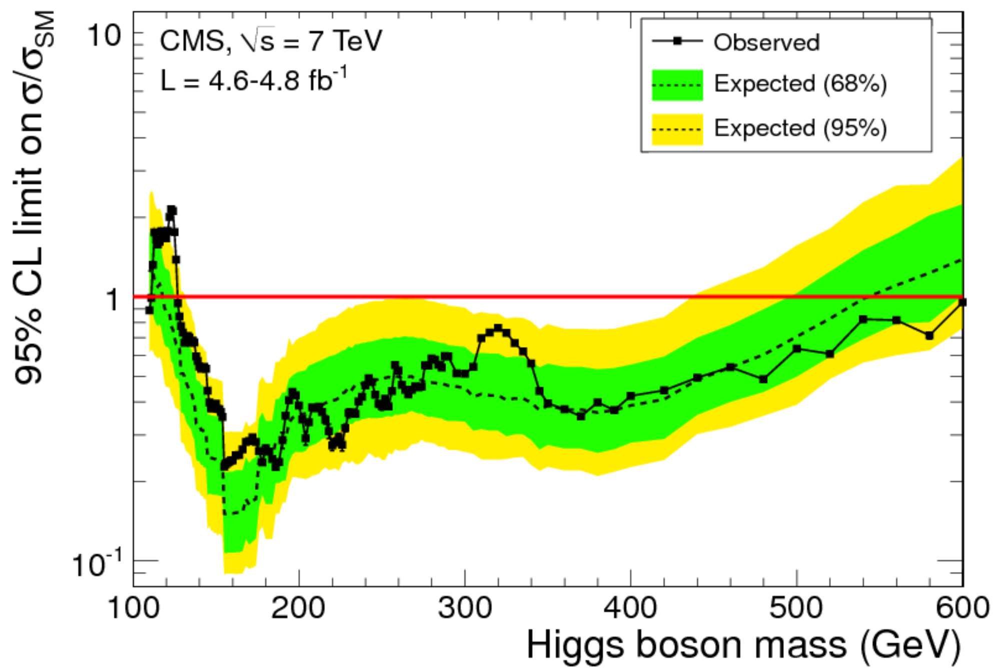
SM Higgs couplings to all SM particles are fixed by the mass-generation mechanism $\rightarrow$ variation with $M_h$ is due to kinematics.




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.

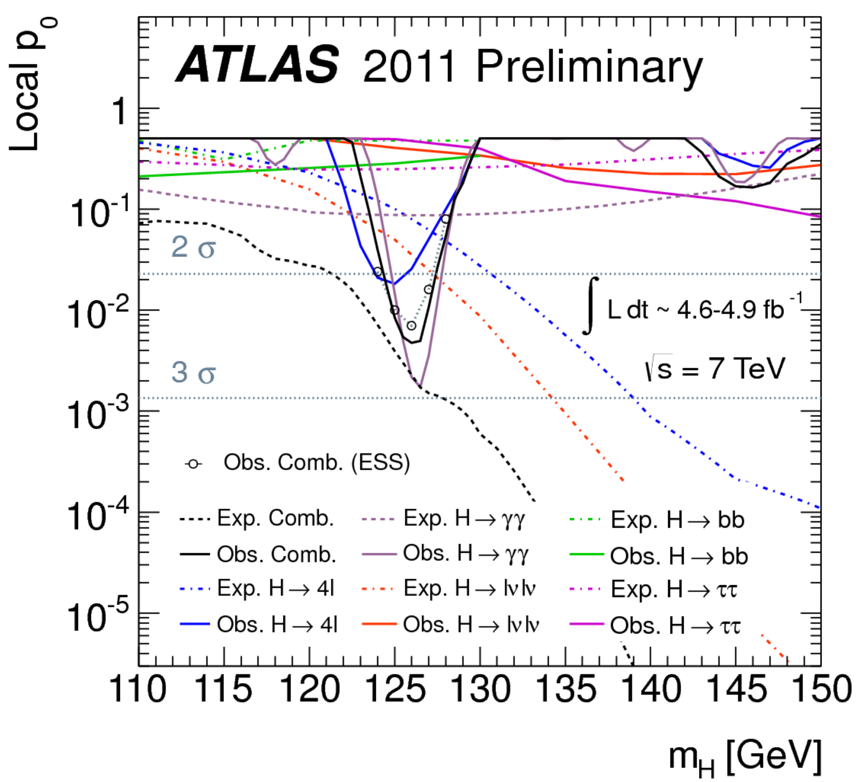
SM Higgs exclusion from ATLAS and CMS:

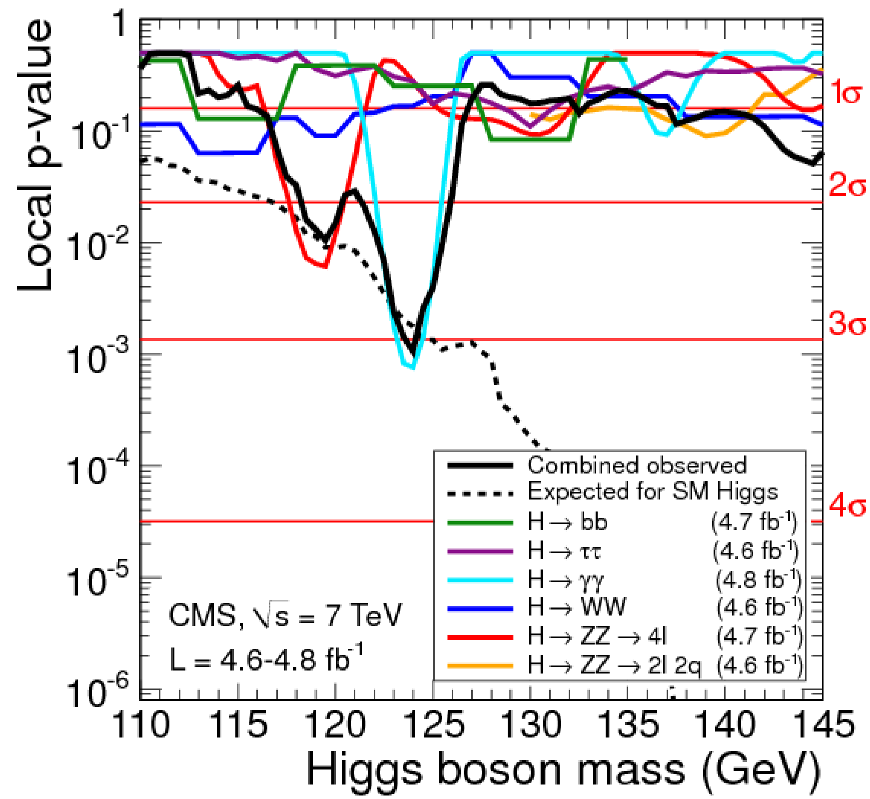



- SM Higgs excluded for masses between about 130 and 600 GeV
- SM Higgs below 114 GeV excluded by LEP
- SM Higgs above 600 GeV strongly disfavoured by precision electroweak measurements

Small excess around 125 GeV consistent with SM Higgs




ATLAS: $\gamma\gamma$ and $4\ell$ (from $ZZ^*$) final states

CMS: $\gamma\gamma$ final state

About 2–3$\sigma$ in each experiment

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

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

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

Tightly constrained by $\rho$ 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:

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

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

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

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.

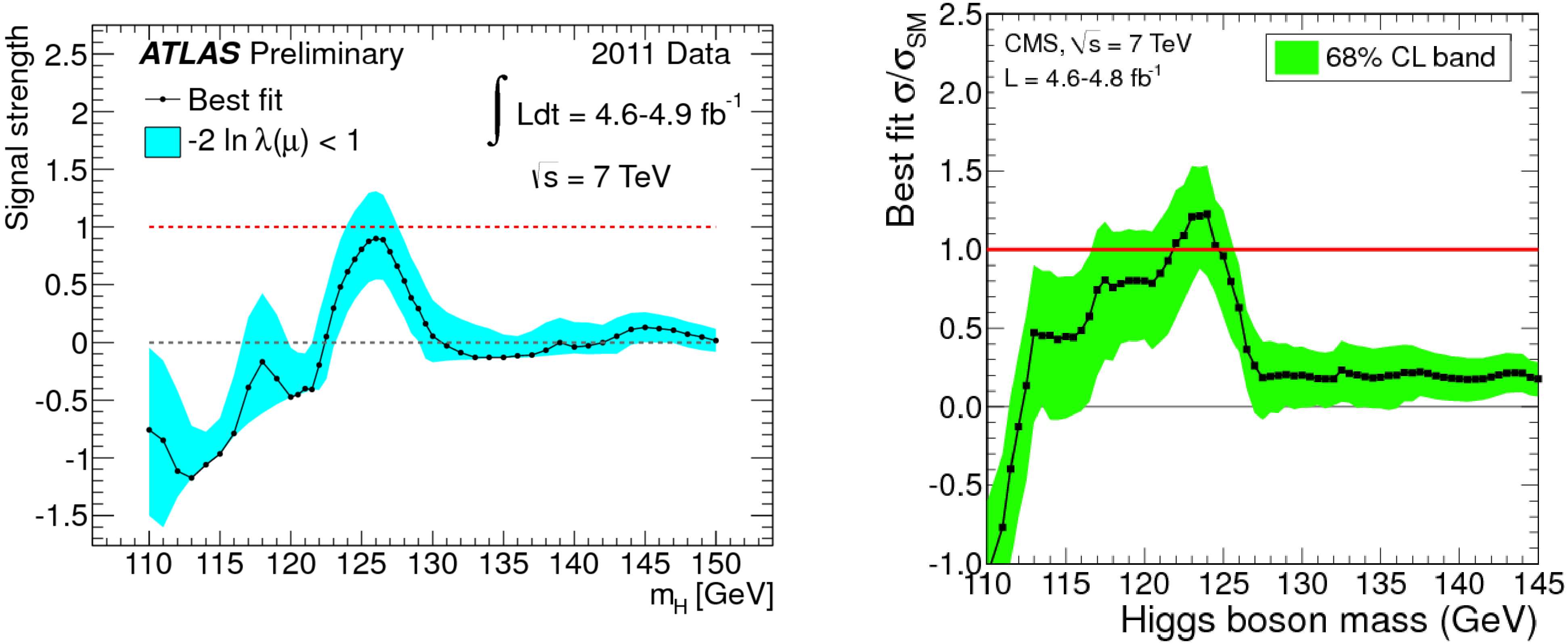
- New coloured or charged particles give new loop contributions.
  e.g. top squark, charginos, charged Higgs in MSSM

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

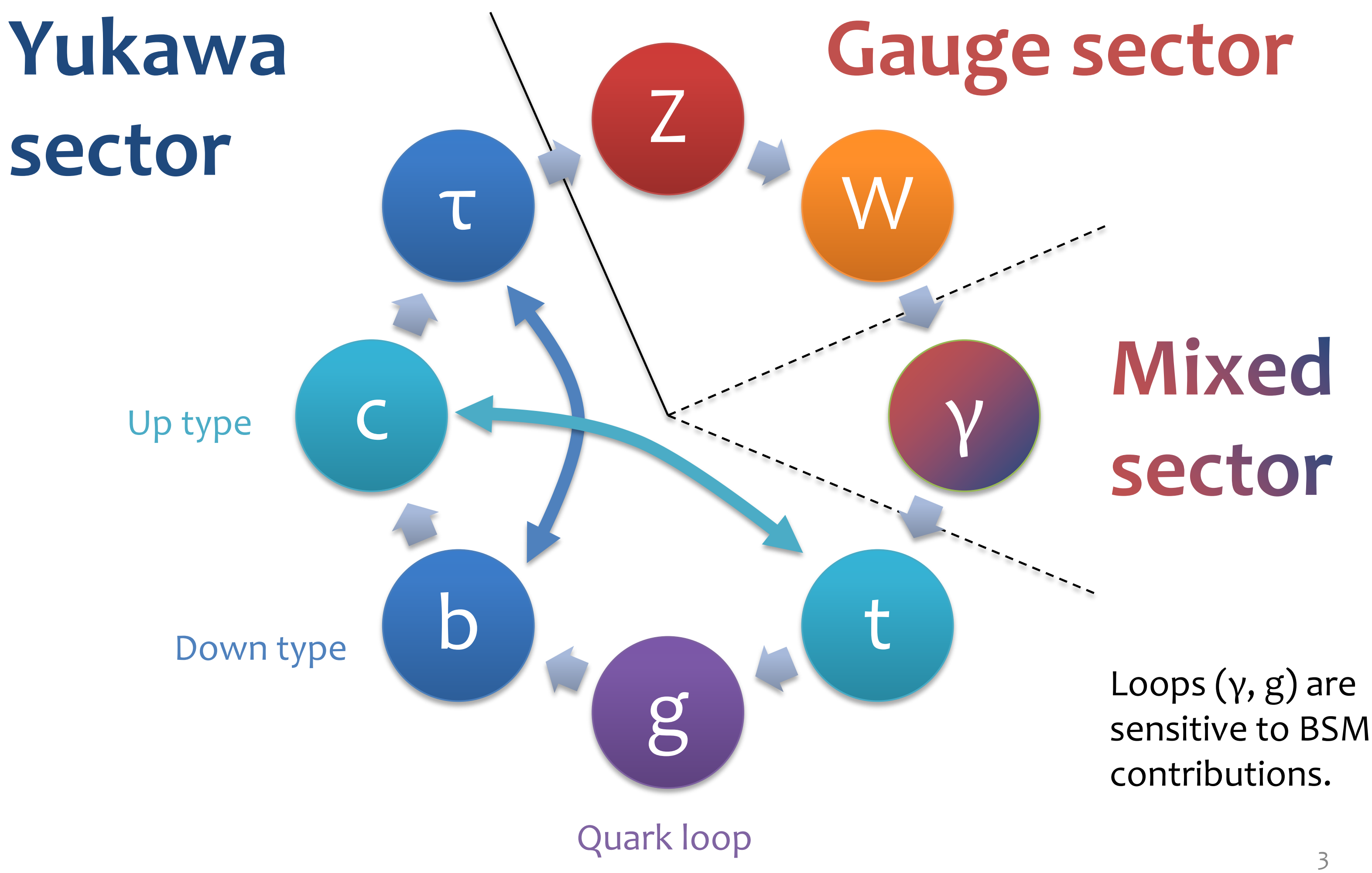
$\Rightarrow$ Treat $\bar{g}_g$ and $\bar{g}_\gamma$ as additional independent coupling parameters.
Loop-induced effective couplings: momentum-dependence issues at NLO! (more on this later)

# LHC measurements to date

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



# Going beyond a single scaling factor




*Slide from André David, LHC HXSWG Light Mass Higgs subgroup meeting, May 18, 2012*

## 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:

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

Coupling dependence (at leading order):

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

Each rate depends on multiple couplings. $\rightarrow$ correlations

Non-SM decays could also be present:

- invisible final state (can look for this with dedicated searches)
- "unobserved" final state (e.g., $h \rightarrow$ 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 $\Gamma_{\text{tot}}$. $\Gamma_{\text{tot}} \geq \Gamma(h \to WW, ZZ)$

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

## 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 $\Gamma_{\text{tot}}$ 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

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

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

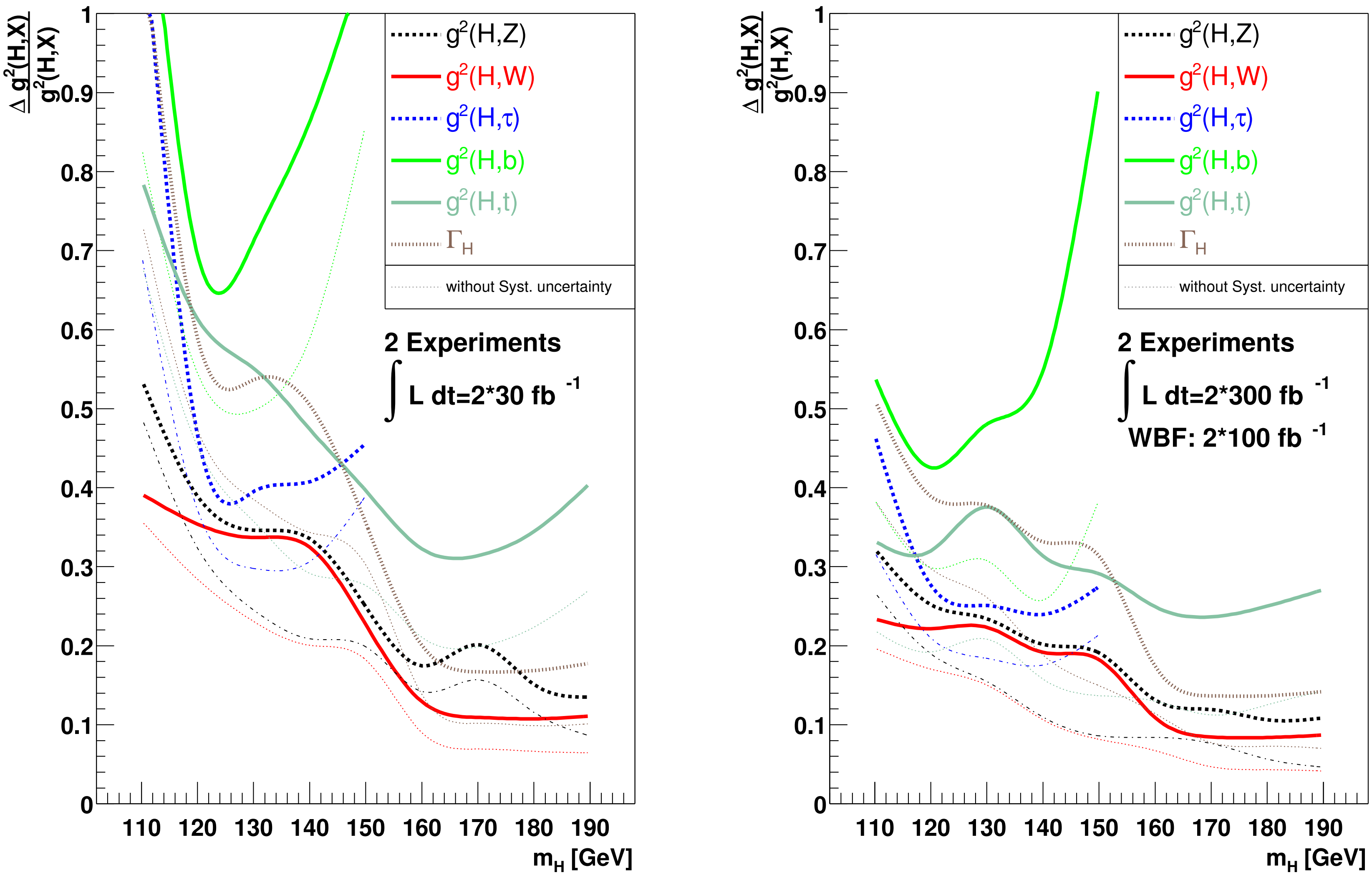
VBF $qqH \to qq\tau\tau$

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)

$t\bar{t}H$, $H \to b\bar{b}$ $\times$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.

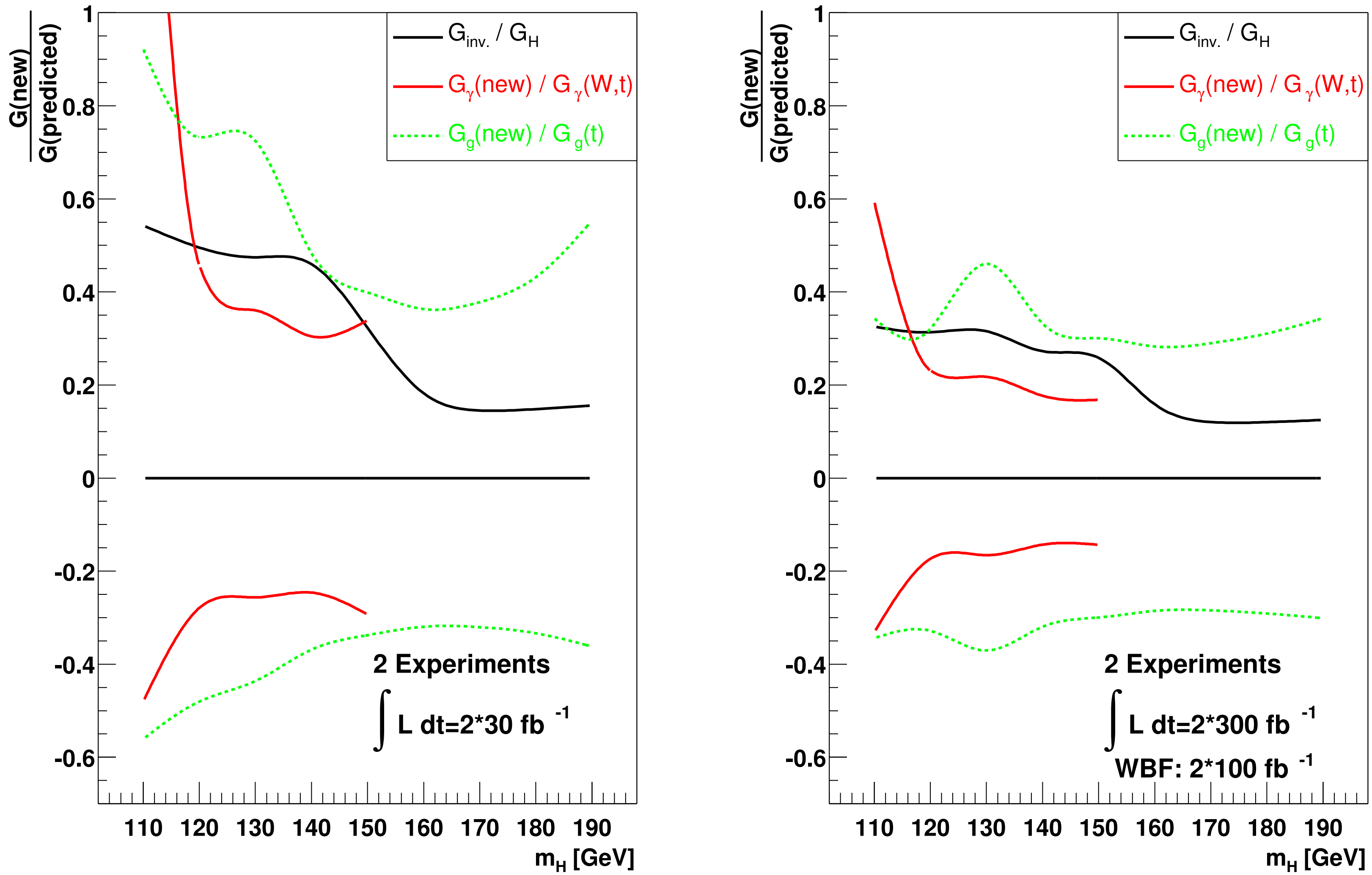
Dührssen, Heinemeyer, HEL, Rainwater, Weiglein, & Zeppenfeld, PRD70, 113009 (2004)




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

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

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 $\Gamma_\gamma$ from $W, t$ loops

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

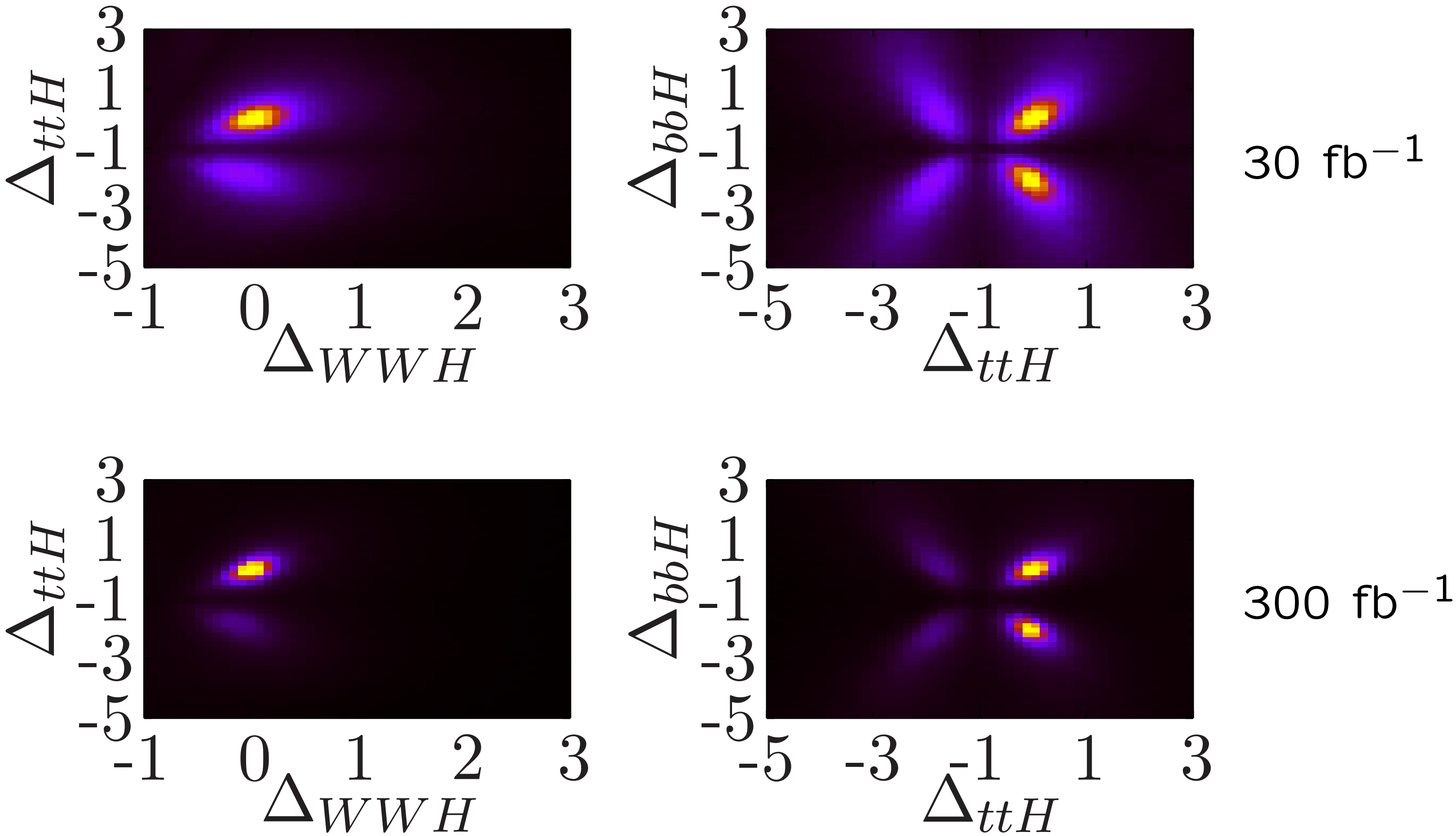
Lafaye, Plehn, Rauch, D. Zerwas, & Dührssen, JHEP 0908, 009 (2009)

- 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)



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:

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

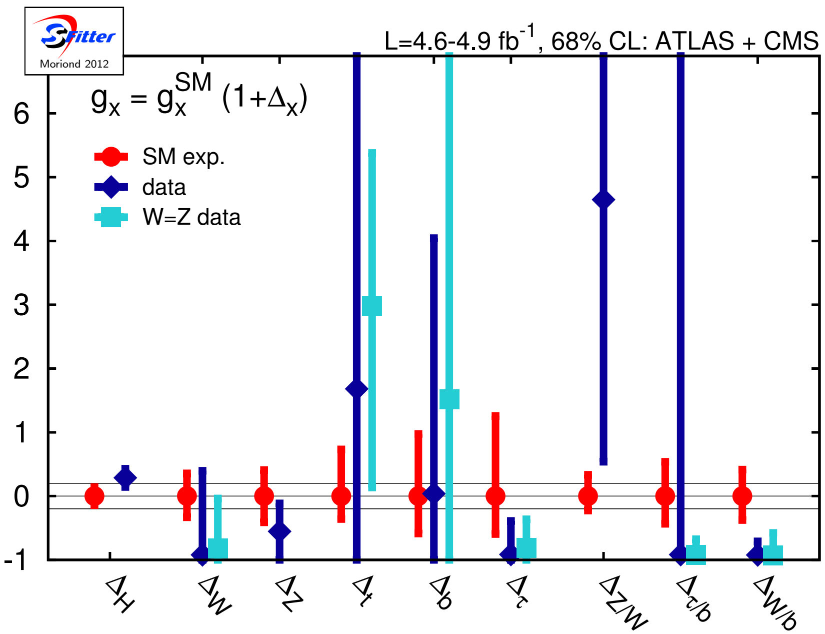
$\Delta_t/\Delta_W : \pm 51\%$ $\Delta_b/\Delta_W : 31\%$ $\Delta_\tau/\Delta_W : 28\%$

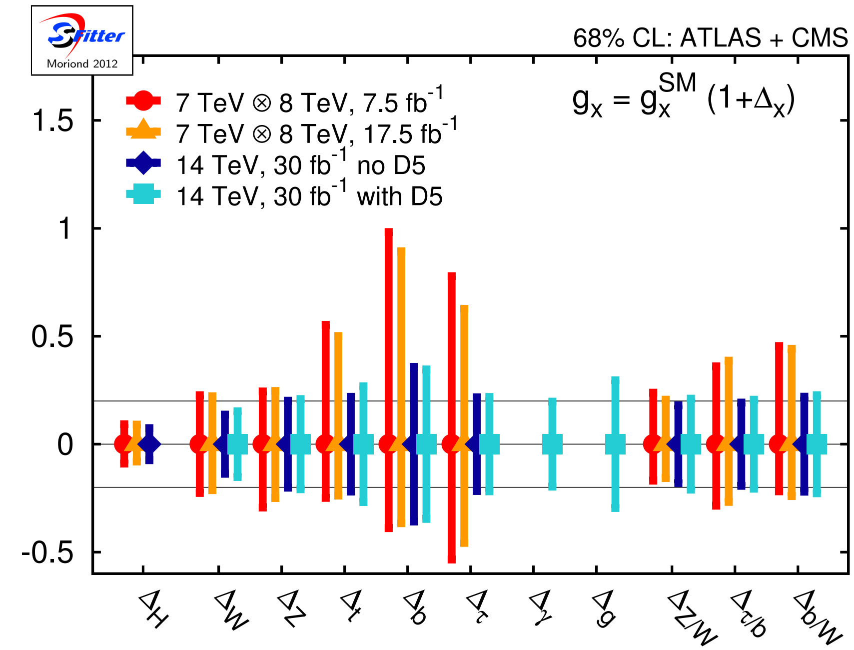
$\Delta_g/\Delta_W : \pm 61\%$ $\Delta_\gamma/\Delta_W : 30\%$

Slight improvement due to correlations.

See also new analysis, Klute, Lafaye, Plehn, Rauch, & D. Zerwas, arXiv:1205.2699

# SFitter new results




"Data" fit ranges much looser than SM expectation due to secondary large-coupling solution which cannot be separated with current data.

Klute, Lafaye, Plehn, Rauch, & D. Zerwas, arXiv:1205.2699

## What do we really 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?

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

## A more mathy way to understand this: the Chiral Lagrangian

Without a Higgs, the SM Lagrangian 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 the $W$ mass and coupling).

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

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

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

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

$\sigma^a$ are the three Pauli spin matrices.

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

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

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

$\Sigma$ is formally dimensionless (in terms of fields).

Let's add powers of an extra scalar field $h$ up to dimension 4:

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \bar{\psi}_i \mathcal{D}_\mu \gamma^\mu \psi_i$$
$$+ (\mathcal{D}_\mu \Sigma)^\dagger (\mathcal{D}^\mu \Sigma) \left(1 + a\frac{2h}{v} + b\frac{h^2}{v^2}\right) - y_{ij}\bar{\psi}_i \Sigma \psi_j \left(1 + c\frac{h}{v}\right)$$

Tree-level unitarity:

$V_L V_L \to V_L V_L$ 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 also unitary 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:

$$\overline{\Sigma} = e^{-i\xi^a(x)\sigma^a/v} \begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix}$$

$\Sigma$ is formally dimensionless (in terms of fields).

Let's add powers of an extra scalar field $h$ up to dimension 4:

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \bar{\psi}_i \mathcal{D}_\mu \gamma^\mu \psi_i$$
$$+ (\mathcal{D}_\mu \Sigma)^\dagger (\mathcal{D}^\mu \Sigma) \left(1 + a\frac{2h}{v} + b\frac{h^2}{v^2}\right) - y_{ij}\bar{\psi}_i \Sigma \psi_j \left(1 + c\frac{h}{v}\right)$$

Composite Higgs:

- Deviations in couplings $a, b, c \neq 1$ ultimately come from higher-dimensional operators: $\sim 1 + \mathcal{O}(v^2/f^2)$

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

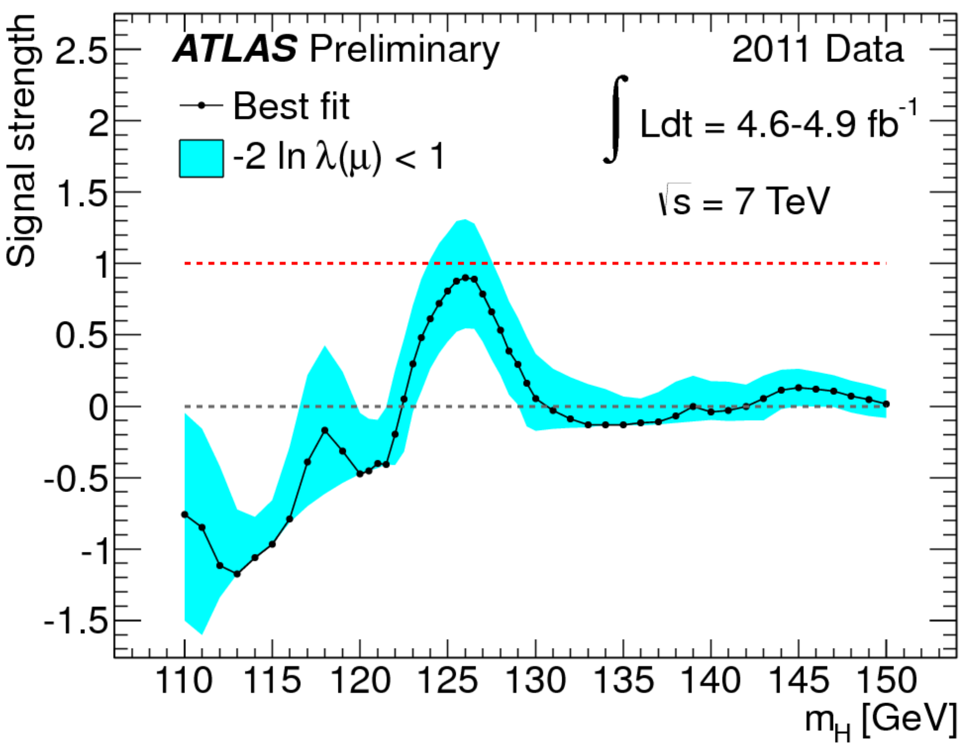
 Note the "decoupling limit": $h \to$ SM-like

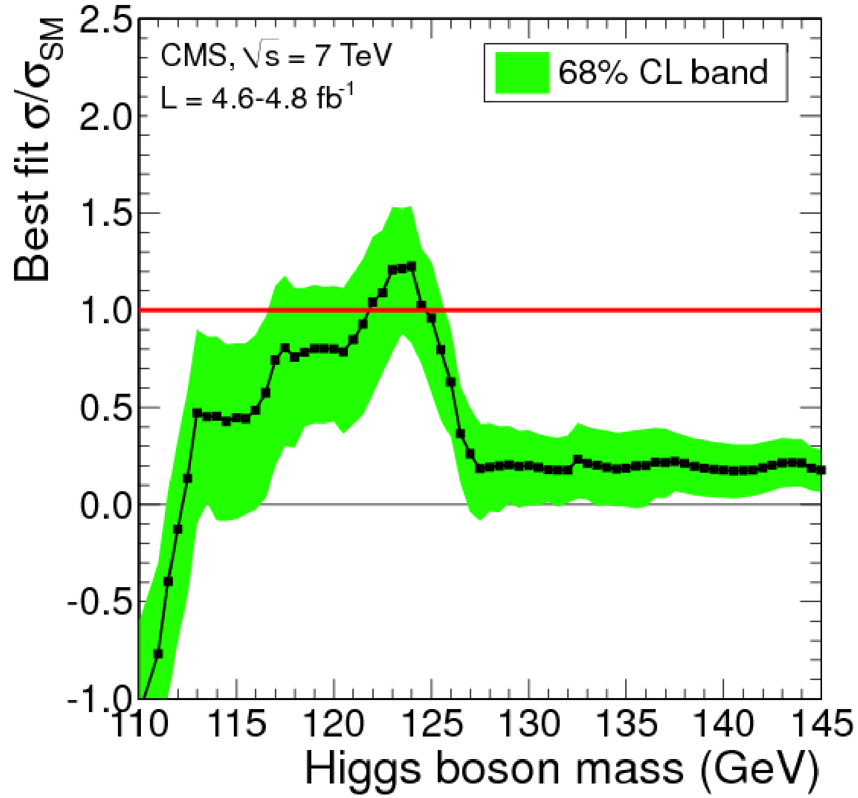
Examples:

- Little Higgs models
- 5-dim Composite Higgs models
- Extended Higgs sectors (after integrating out extra states)

# LHC measurements to date (2011 data)

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




1-parameter "measurement"

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

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

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

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

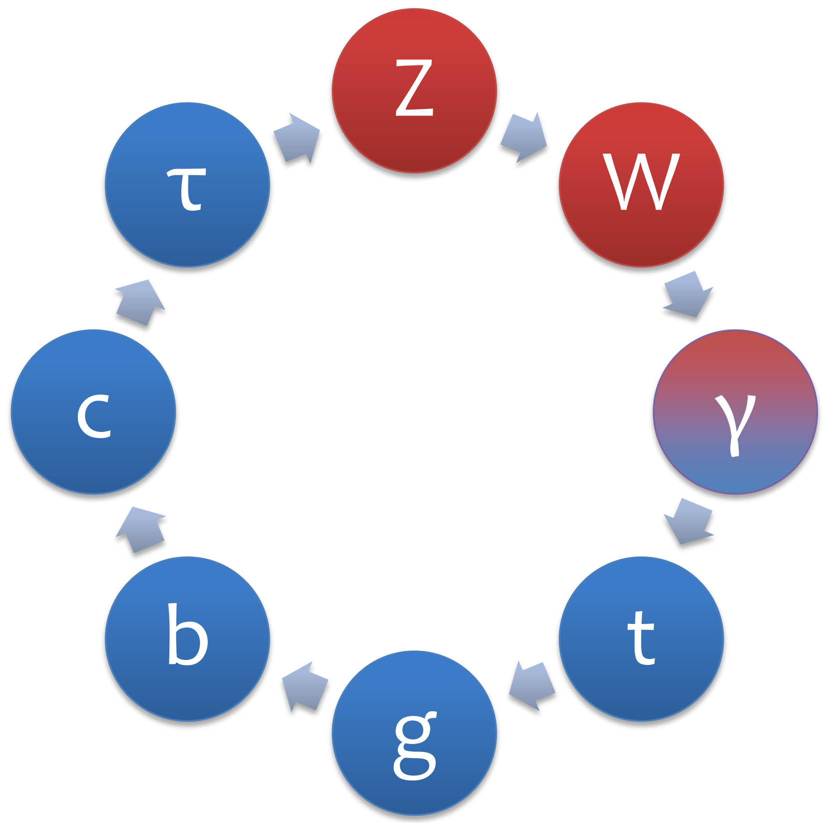
unless new decay mode is picked up by SM signal/background selections and modifies kinematic shapes.

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

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

# SM deconstruction 2

$C_F$, $C_V$




✔ Well-known!

$$\frac{|c\,A_f(m_h) + a\,A_W(m_h)|^2}{|A_f(m_h) + A_W(m_h)|^2}$$

| $m_h$ (GeV) | $A_f$ | $A_W$ |
|---|---|---|
| 100 | -1.81 | 7.72 |
| 110 | -1.82 | 7.93 |
| 120 | -1.83 | 8.19 |
| 130 | -1.84 | 8.53 |

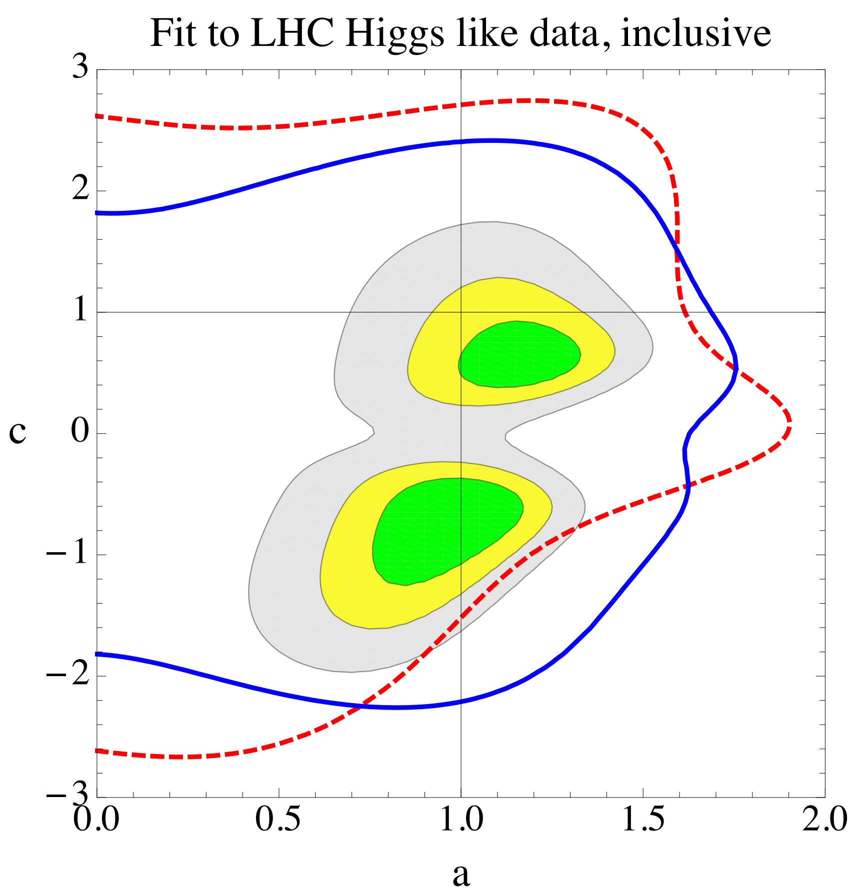
5

*Slide from André David, LHC HXSWG Light Mass Higgs subgroup meeting, May 18, 2012*

# 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: $a = \sqrt{1-\xi}$, $c = \sqrt{1-\xi}$




## Type-I 2HDM:

$a = \sin(\beta - \alpha)$
$c = \cos\alpha / \sin\beta$

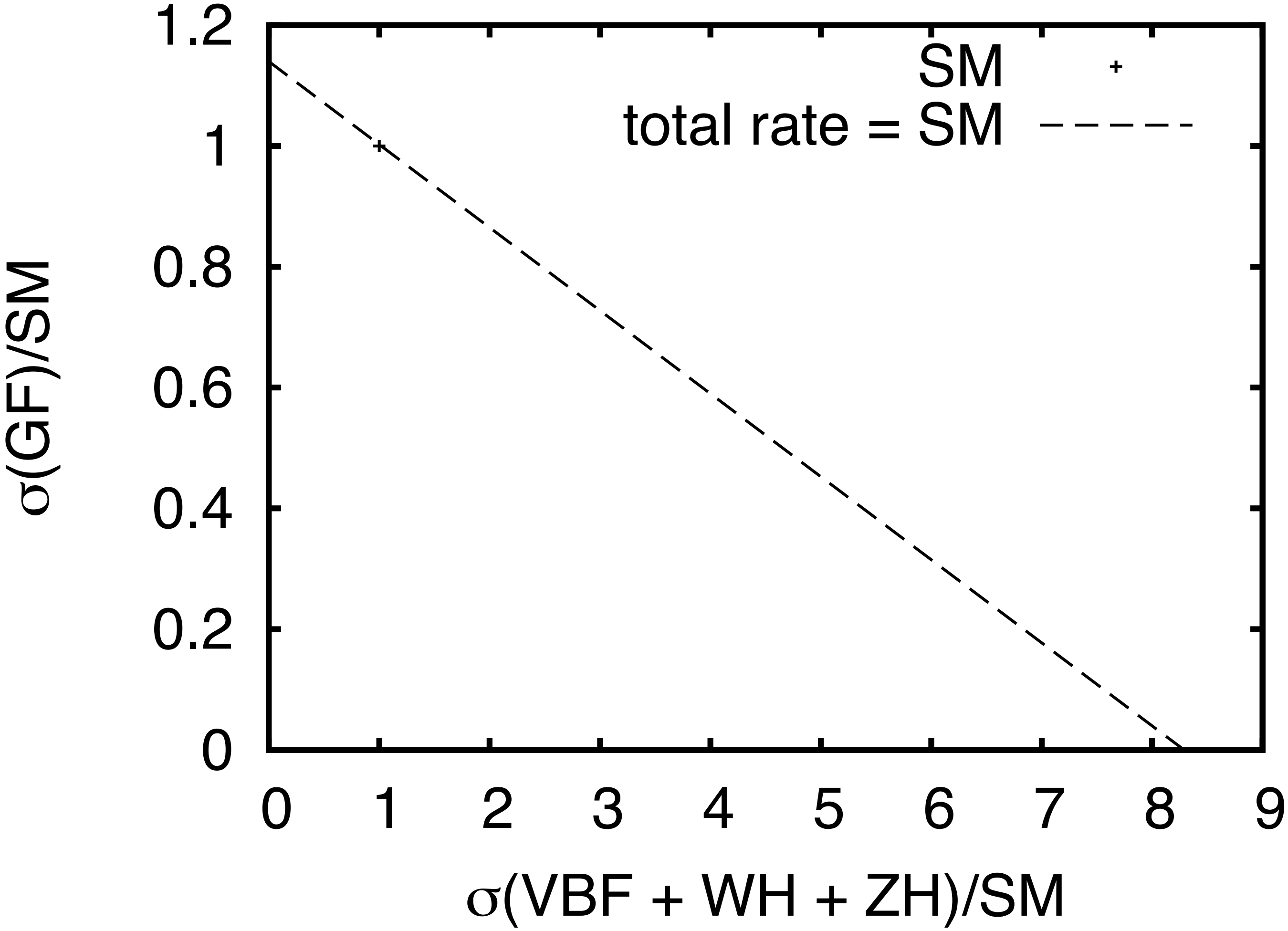
Small difference:
$H^+$ gives small additional contribution to $h \to \gamma\gamma$ loop

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

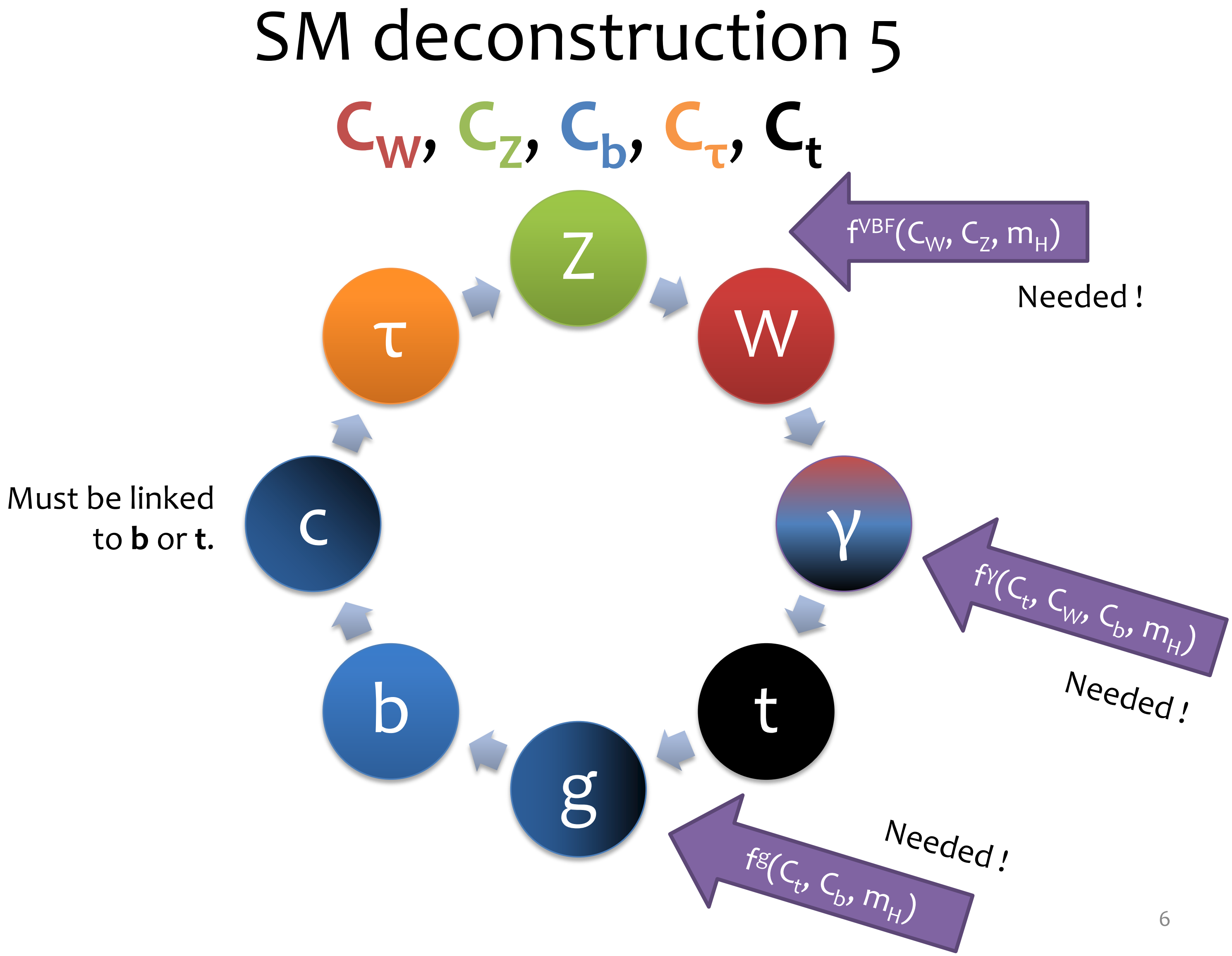
Espinosa, Grojean, Mühlleitner & Trott, 1202.3697 [hep-ph]

## Beware theorists bearing VBF fits!

A two-parameter proposal for presenting signal rates:



Going beyond two parameters: the full fit

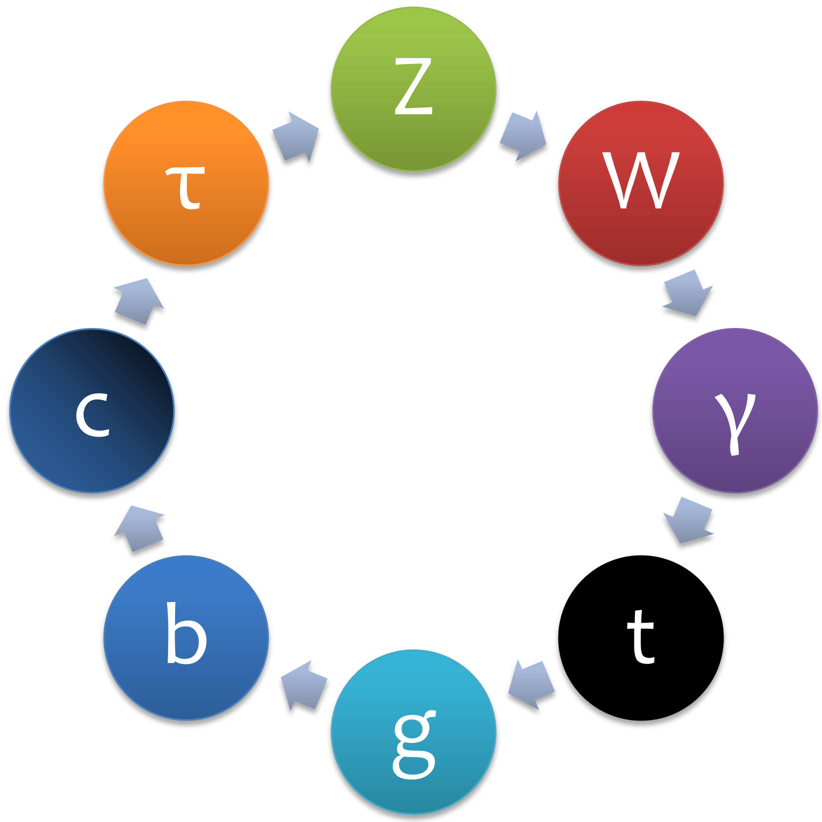



*Slide from André David, LHC HXSWG Light Mass Higgs subgroup meeting, May 18, 2012*

Going beyond two parameters: the full fit

# Floating loops 5+2

$C_W$, $C_Z$, $C_b$, $C_\tau$, $C_t$ + $C_\gamma$, $C_g$




Must be linked to **b** or **t**.

9

*Slide from André David, LHC HXSWG Light Mass Higgs subgroup meeting, May 18, 2012*

## 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 $h \to \gamma\gamma$ 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.

## 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.

# Conclusions

LHC data from 2011 has made theorists very excited.
2012 data will tell us whether a Higgs is really there or not.

If the Higgs is there, LHC data will eventually let us measure Higgs couplings to $WW$, $ZZ$, $t\bar{t}$, $b\bar{b}$, $\tau\tau$, $gg$, $\gamma\gamma$.

Semi-model-independent fit is very valuable, but fits in few-parameter extended-Higgs models will also be useful.

Close interaction between theorists and experimentalists is always a good thing.
- Light Mass Higgs subgroup of LHC Higgs Cross Section Working Group (see the CERN twiki)

BACKUP SLIDES

## 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 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 $y_t$.

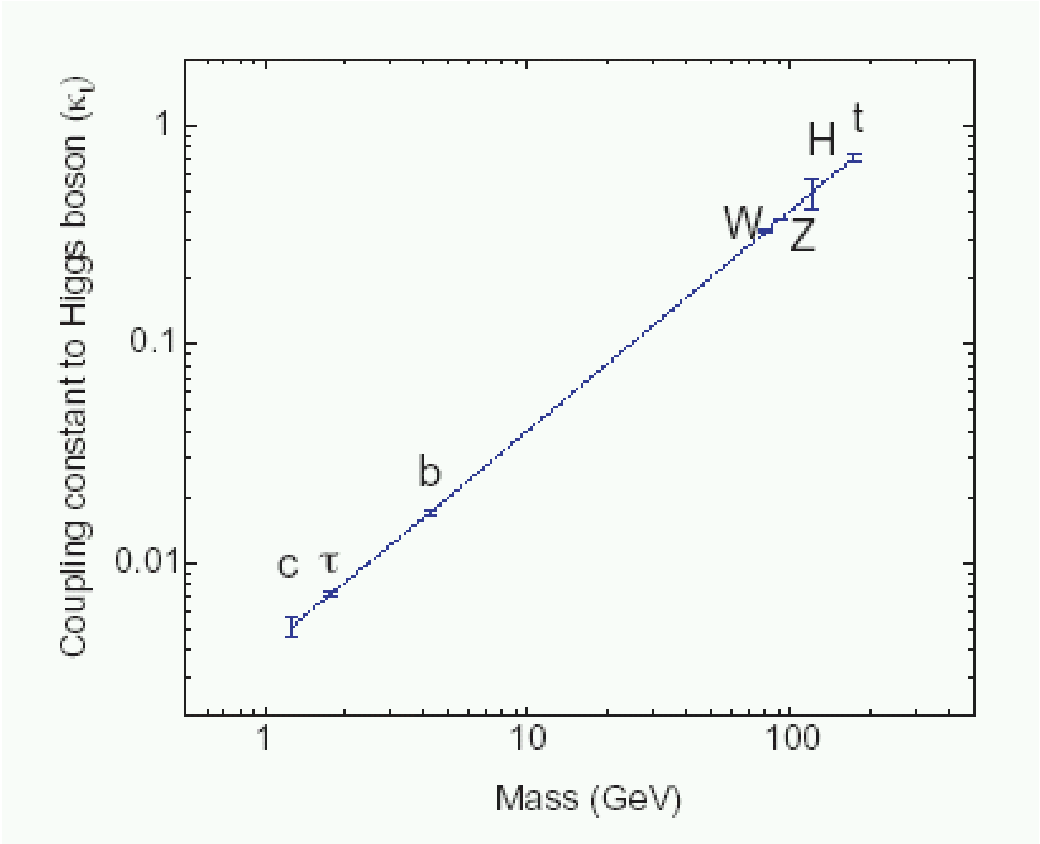
- Nonstandard production modes like $b\bar{b} \to h$.

- $\sigma(A \to h) * \mathrm{BR}(H \to X) \propto \Gamma_A \Gamma_X / \Gamma_{\mathrm{tot}}$ is not strictly true at NLO: different kinematics in production and decay can shift relative contributions of underlying couplings.

To test SM Higgs mechanism, need to measure Higgs couplings.

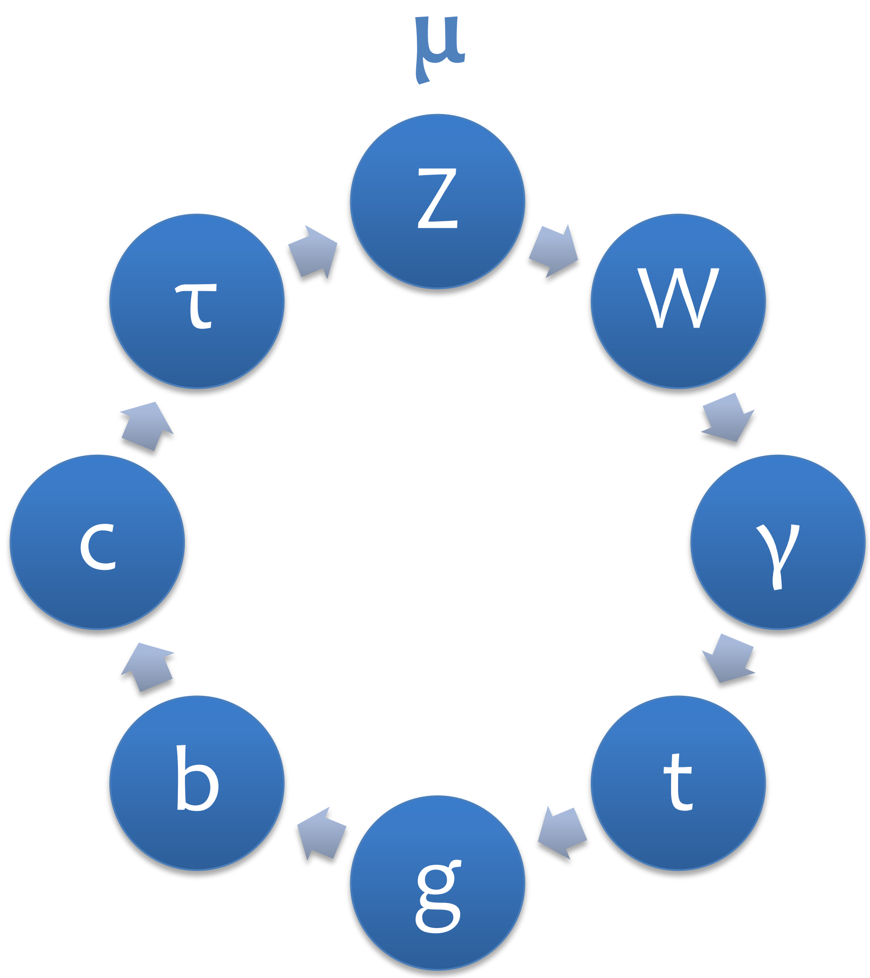
SM: coupling of Higgs to each SM particle already fixed by known particle masses.

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




ACFA report

# One global scale (2011)




2

*Slide from André David, LHC HXSWG Light Mass Higgs subgroup meeting, May 18, 2012*