Couplings of the Higgs-like particle

Bogdan Dobrescu (*Fermilab*)

Work with Joe Lykken: *1210.3342*

Outline:
- **Non-standard decays**
- **Upper & lower limits on the Higgs width and couplings**
- **Non-standard production**

Talk at the LHC Workshop – University of Chicago - Nov. 14, 2012

A Higgs boson is defined as any scalar particle h^0 that couples to the W and Z according to:

$$\frac{g}{M_W} h^0 \left(C_W M_W^2 W^+ W^- + C_Z \frac{M_Z^2}{2} Z Z \right)$$

g is the $SU(2)_W$ gauge coupling.

C_W and C_Z parametrize the deviation from the SM couplings:

$$C_W^{\mathrm{SM}} = C_Z^{\mathrm{SM}} = 1$$

Couplings of a Higgs boson to 3rd generation fermions:

$$-C_t \frac{m_t}{v} h^0 \bar{t}t - C_b \frac{m_b}{v} h^0 \bar{b}b - C_\tau \frac{m_\tau}{v} h^0 \bar{\tau}\tau$$

C_t, C_b, C_τ are real parameters, equal to 1 in the SM. $v \approx 246$ GeV

Higgs coupling to a pair of gluons is given by a dimension-5 operator:

$$C_g \frac{\alpha_s}{12\pi v} h^0 G^{\mu\nu} G_{\mu\nu}$$

Effective coupling to photons:

$$C_\gamma \equiv \left(\frac{\Gamma(h^0 \to \gamma\gamma)}{\Gamma^{\rm SM}(h^0 \to \gamma\gamma)} \right)^{1/2}$$

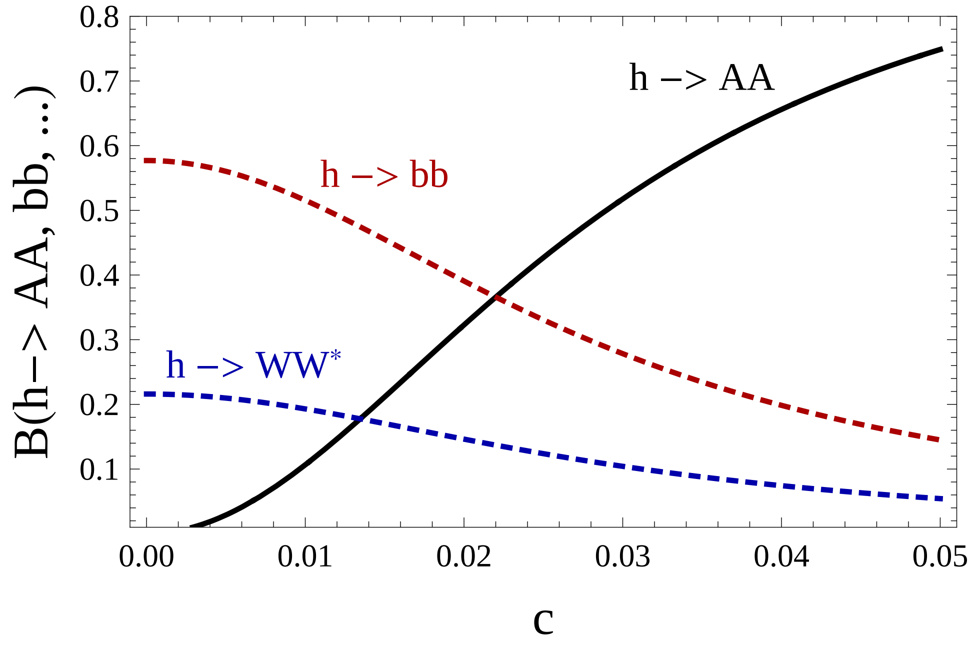
Nonstandard Higgs decays

Standard model + a gauge-singlet complex scalar S:

$$S = \frac{1}{\sqrt{2}} \left(\varphi_S + \langle S \rangle\right) e^{iA^0/\langle S \rangle} \quad , \; A^0 \text{ is a CP-odd spin-0 particle}$$

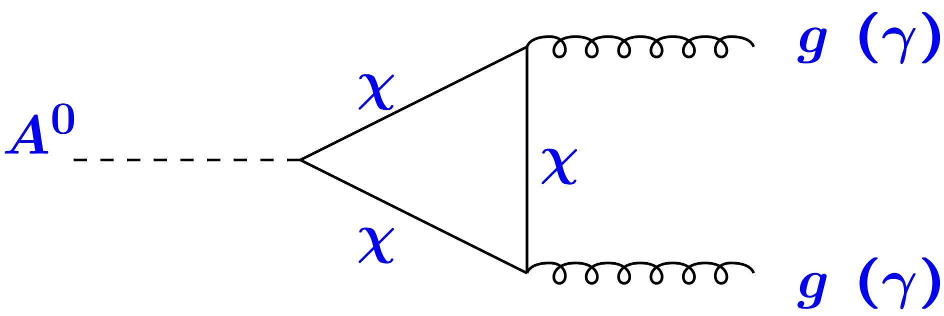
$$\frac{c\, v}{2} h^0 A^0 A^0 \;\text{coupling} \;\Rightarrow\; \Gamma(h^0 \to A^0 A^0) = \frac{c^2\, v^2}{32\pi M_h} \left(1 - 4\frac{M_A^2}{M_h^2}\right)^{1/2}$$

For $2M_A \ll M_h = 125$ GeV:



A^0 decays are model dependent.

Example: *(Dobrescu, Landsberg, Matchev, hep-ph/0005308)*



χ is a vector-like quark.

If $M_A > 1$ GeV:
$\mathcal{B}(A^0 \to gg) \gtrsim 99\%$.

Even $\mathcal{B}(h \to A^0 A^0 \to 4\, g)$ near 100% is very hard to observe due to huge backgrounds.

Total width Γ_h of the Higgs-like particle may be $\gg$ the sum over the partial widths of the SM decays.

$\mathcal{B}(A^0 \to \gamma\gamma) \lesssim 1\%$, **but $h \to A^0 A^0 \to \gamma\gamma jj$ may still be eventually observed at the LHC.** *(Chang, Fox, Weiner, hep-ph/0608310, A. Martin hep-ph/0703247 ...)*

Cross section $\times$ branching fractions:

$$\sigma(pp \to h + X \to ... + X) \propto \frac{1}{\Gamma_h}$$

Rate measurements give: $\dfrac{C^2_{\text{prod.}}\, C^2_{\text{decay}}}{\Gamma_h}$

D. Zeppenfeld, et al, hep-ph/0002036,

V. Barger, M. Ishida, W.-Y. Keung 1203.3456,...

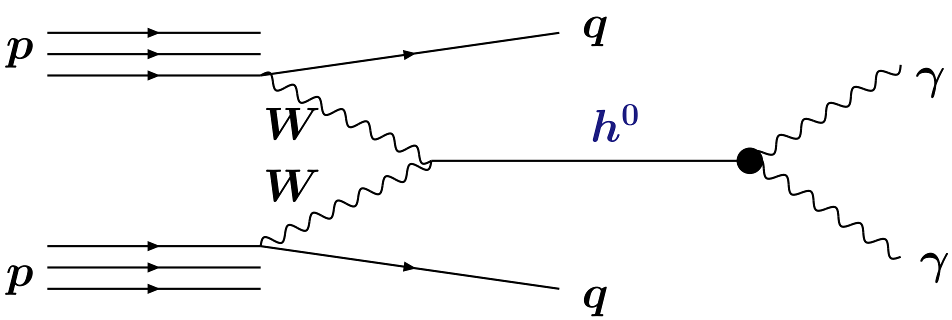
Observables:

$$a_{\mathcal{P}} \equiv C^2_{\mathcal{P}} \left(\frac{\Gamma_h^{\text{SM}}}{\Gamma_h}\right)^{1/2} \quad , \quad \text{for } \mathcal{P} = W, Z, g, \gamma, Z\gamma, t, b, \tau$$

How can we extract the Higgs couplings?

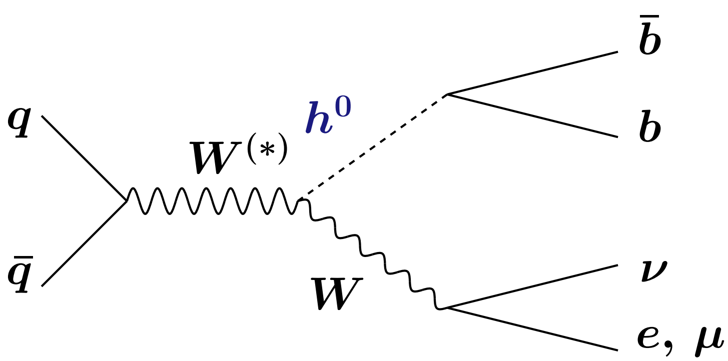
E.g., an increase in all couplings can be compensated by a larger Γ_h due to (almost) undetectable decays through new particles.

First, extract the $a_{\mathcal{P}}$ observables from the rate measurements:



$$\left(\frac{\sigma}{\sigma_{\rm SM}}\right)(hjj \to \gamma\gamma jj) = \frac{a_W + r a_Z}{1+r}\, a_\gamma$$

$r \approx 0.3$



$$\left(\frac{\sigma}{\sigma_{\rm SM}}\right)(Wh \to Wb\bar{b}) = a_W\, a_b$$

$$\left(\frac{\sigma}{\sigma_{\rm SM}}\right)(Wh \to WWW) = a_W^2$$

...

Then, make a mild theoretical assumption ...

If electroweak symmetry breaking is due entirely to VEVs of $SU(2)_W$ doublets, then:

$$0 < C_W = C_Z \leq 1$$

If triplets or higher $SU(2)_W$ representations have VEVs, it is possible to have $C_W \neq C_Z$, and values for $C_W, C_Z > 1$.

Even then one can derive some upper bounds (~ 1.5) on the couplings:

$$|C_W| < C_W^{\max} \quad , \quad |C_Z| < C_Z^{\max}$$

Can be directly tested at the LHC through searches for H^{++}, ...

Upper limit on Γ_h

The upper limits on C_W and C_Z imply

$$\Gamma_h \le \Gamma_h^{\max} = \mathrm{Min}\left\{ \frac{(C_W^{\max})^4}{a_W^2}, \frac{(C_Z^{\max})^4}{a_Z^2} \right\} \Gamma_h^{\mathrm{SM}}$$

If the electroweak symmetry is broken only by the VEVs of $SU(2)_W$ doublets (majority of known theories), then

$$\Gamma_h \le \Gamma_h^{\max} = \frac{\Gamma_h^{\mathrm{SM}}}{a_V^2}$$

where $a_W = a_Z \equiv a_V$.

h^0 decay	h^0 production	observable	measured $\sigma/\sigma_{\rm SM}$; $M_h = 125$ GeV
WW^*	$gg \to h^0$	$a_g a_W$	1.3 ± 0.5, ATLAS ; 126 GeV 0.74 ± 0.25 , CMS $0.8^{+0.9}_{-0.8}$, Tevatron our average: 0.85 ± 0.22
	VBF	$(a_W + r a_Z)/(1+r)\, a_W$	$0.3^{+1.5}_{-1.6}$, CMS
	$W^* \to W h^0$	a_W^2	$-2.9^{+3.2}_{-2.9}$, CMS
	$Z^* \to Z h^0$	$a_Z a_W$	
ZZ^*	$gg \to h^0$	$a_g a_Z$	$1.3^{+0.7}_{-0.5}$, ATLAS $0.8^{+0.35}_{-0.28}$, CMS ; 126 GeV our average: $0.96^{+0.31}_{-0.26}$
	VBF	$(a_W + r a_Z)/(1+r)\, a_Z$	
$\gamma\gamma$	$gg \to h^0$	$a_g a_\gamma$	1.7 ± 0.6 , ATLAS ; 126.5 GeV 1.4 ± 0.6 , CMS $6.1^{+3.3}_{-3.2}$, Tevatron our average: 1.6 ± 0.4
	VBF	$(a_W + r a_Z)/(1+r)\, a_\gamma$	2.6 ± 1.3 , ATLAS ; 126.5 GeV $2.1^{+1.4}_{-1.1}$, CMS our average: $2.3^{+1.0}_{-0.9}$

Combine the $gg \to h^0 \to WW^*, ZZ^*$ rate measurements

$$(\sigma/\sigma_{\rm SM})(gg \to h \to VV^*) = 0.89 \pm 0.17$$

For $C_W = C_Z$,

$$a_V^2 = (\sigma/\sigma_{\rm SM})(gg \to h \to VV^*) \frac{(\sigma/\sigma_{\rm SM})({\rm VBF} \to hjj \to \gamma\gamma jj)}{(\sigma/\sigma_{\rm SM})(gg \to h \to \gamma\gamma)}$$

Using (bifurcated) Gaussian distributions,

$$a_V = 1.10^{+0.35}_{-0.26}$$

This implies:

$$\Gamma_h \leq \Gamma_h^{\rm max} = 0.58^{+0.82}_{-0.11}\ \Gamma_h^{\rm SM}$$

Lower limit on Γ_h

A lower limit on Γ_h can be derived from the rates required for its observation.

$$\Gamma_h = \sum_{\substack{\mathcal{P}=W,Z,\\ b,\tau,g,\gamma}} C_{\mathcal{P}}^2 \, \Gamma^{\rm SM}(h^0 \to \mathcal{P}\mathcal{P}) + \Gamma_X$$

Γ_X is the h^0 partial decay width into final states other than the SM ones.

Given that $\Gamma_X \geq 0$,

$$\Gamma_h \geq \Gamma_h^{\rm min} = \left(\sum_{\substack{\mathcal{P}=W,Z,\\ b,\tau,g,\gamma}} a_{\mathcal{P}} \, \mathcal{B}^{\rm SM}(h^0 \to \mathcal{P}\mathcal{P}) \right)^2 \Gamma_h^{\rm SM}$$

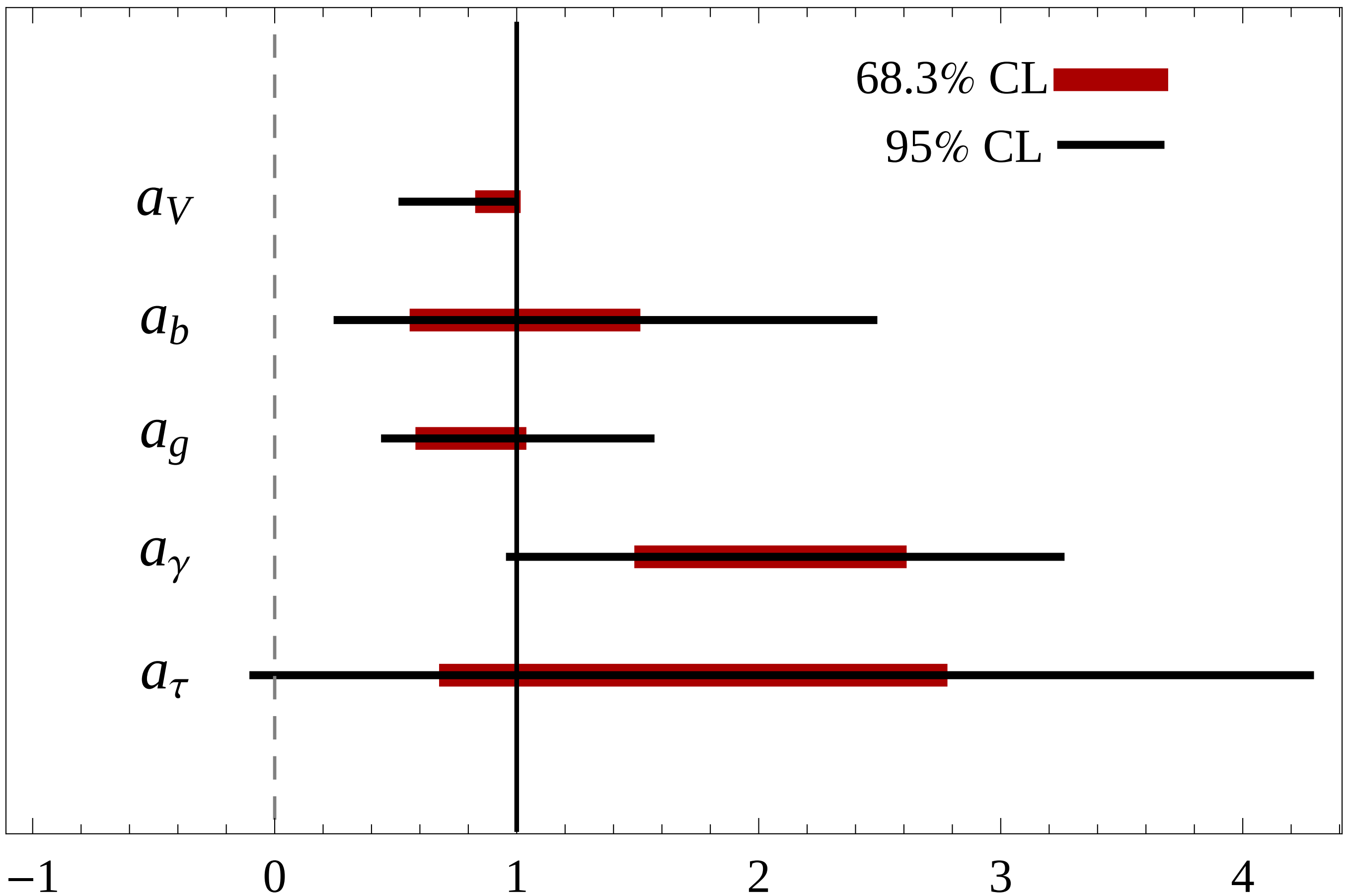
h^0 decay	h^0 production	observable	measured $\sigma/\sigma_{\rm SM}$; $M_h = 125$ GeV
$b\bar{b}$	$W^* \to W h^0$	$a_W a_b$	-0.3 ± 1.0 , ATLAS ; 126 GeV $1.3^{+0.7}_{-0.6}$, CMS $1.56^{+0.72}_{-0.73}$, Tevatron our average: 1.1 ± 0.4
	$Z^* \to Z h^0$	$a_Z a_b$	
	$t\bar{t}h^0$	$a_t a_b$	$-0.8^{+2.1}_{-1.9}$, CMS
$\tau^+\tau^-$	$gg \to h^0$	$a_g a_\tau$	2.4 ± 1.5 ??? , ATLAS $0.9^{+0.8}_{-0.9}$, CMS $2.1^{+2.2}_{-1.9}$, Tevatron our average: 1.3 ± 0.7
	VBF	$(a_W + r a_Z)/(1+r)\, a_\tau$	-0.4 ± 1.5 ??? , ATLAS 0.7 ± 0.8 , CMS
	$W^* \to W h^0$	$a_W a_\tau$	? , ATLAS $1.0^{+1.7}_{-2.0}$, CMS
	$Z^* \to Z h^0$	$a_Z a_\tau$	

Lower limit on the width:

$$\Gamma_h \geq \Gamma_h^{\rm min} = 0.97^{+0.68}_{-0.28}\ \Gamma_h^{\rm SM}$$

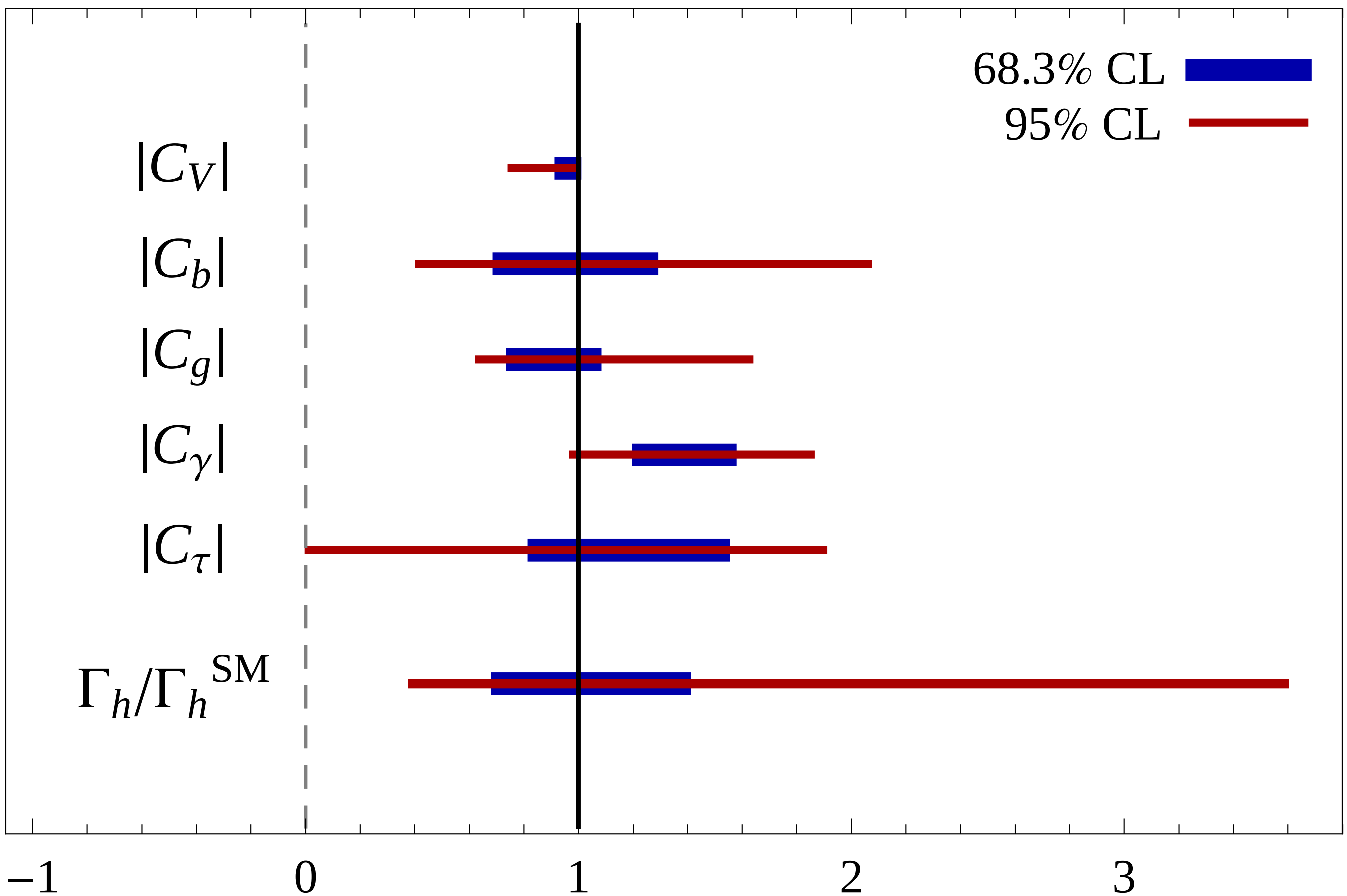
$$a_{\mathcal{P}} = C_{\mathcal{P}}^2 \left(\frac{\Gamma_h^{\mathrm{SM}}}{\Gamma_h} \right)^{1/2}$$

Intervals for ‘apparent squared-couplings’:



$$a_{\mathcal{P}}^{1/2}\left(\frac{\Gamma_h^{\min}}{\Gamma_h^{\rm SM}}\right)^{1/4} < C_{\mathcal{P}} < a_{\mathcal{P}}^{1/2}\left(\frac{\Gamma_h^{\max}}{\Gamma_h^{\rm SM}}\right)^{1/4}$$

Coupling ‘spans’:



Dobrescu, Lykken: 1210.3342

Branching fraction of exotic decays:

(non-SM particles, $c\bar{c}$, ...)

$$\mathcal{B}_X = 1 - \frac{1}{\Gamma_h} \sum_{\substack{\mathcal{P} = W, Z, \\ b, \tau, g, \gamma}} C_{\mathcal{P}}^2 \, \Gamma^{\mathrm{SM}}(h^0 \to \mathcal{P}\mathcal{P})$$

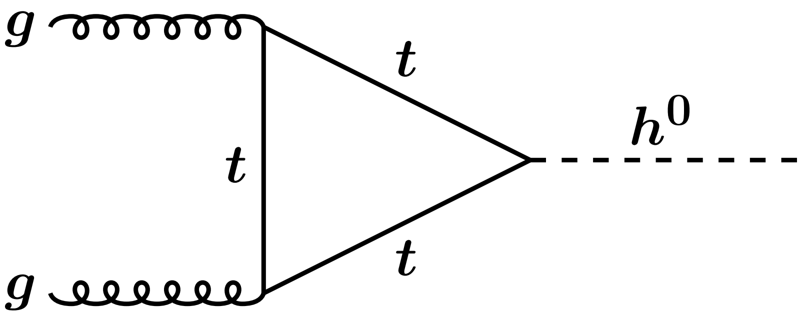
$$\Rightarrow \quad \mathcal{B}_X \leq \mathcal{B}_X^{\max} = 1 - \left(\frac{\Gamma_h^{\mathrm{SM}}}{\Gamma_h^{\max}}\right)^{1/2} \sum_{\substack{\mathcal{P} = W, Z, \\ b, \tau, g, \gamma}} a_{\mathcal{P}} \, \mathcal{B}^{\mathrm{SM}}(h^0 \to \mathcal{P}\mathcal{P})$$

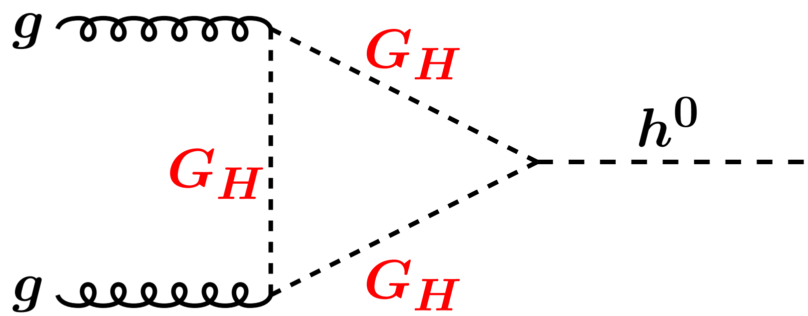
$\mathcal{B}_X^{\max} < 16\%$ **at the 68% CL**

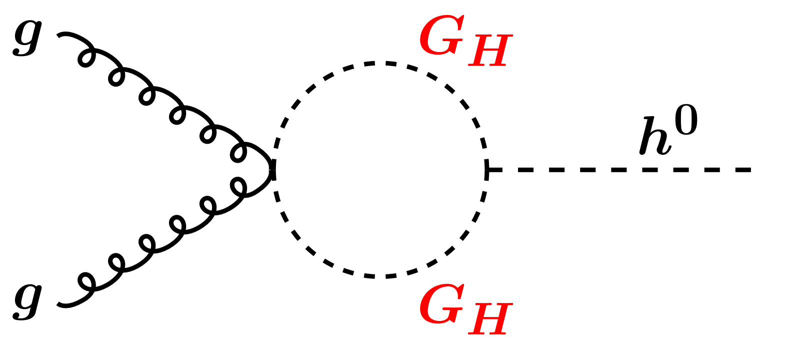
$\mathcal{B}_X^{\max} < 41\%$ **at the 95% CL.**

Non-standard Higgs production

Standard-Model gluon fusion $\pm$ non-standard contributions







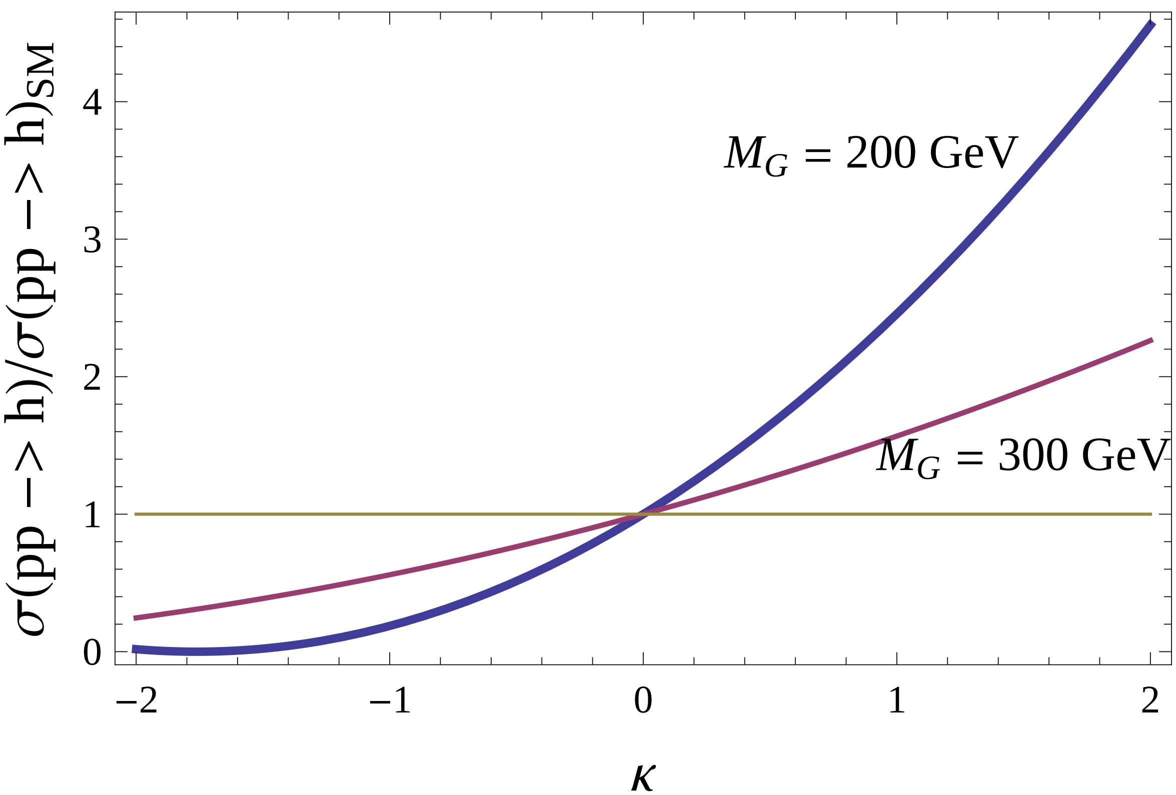
$\kappa \, G_H^a G_H^a H^\dagger H$

The cross section for gluon fusion is reduced (increased) for $\kappa < 0$ (> 0).

Effect may be large for M_{G_H} near the electroweak scale.

For $M_h^2 \ll M_{G_H}^2$: $\quad C_g \approx 1 + 3\kappa \frac{v^2}{8M_{G_H}^2}$

Change in Higgs production through gluon fusion:



Dobrescu, Kribs, Martin: 1112.2208

(see also Bai, Fang, Hewett 1112.1964; Kumar, Vega-Morales, Yu 1205.4244)

Conclusions

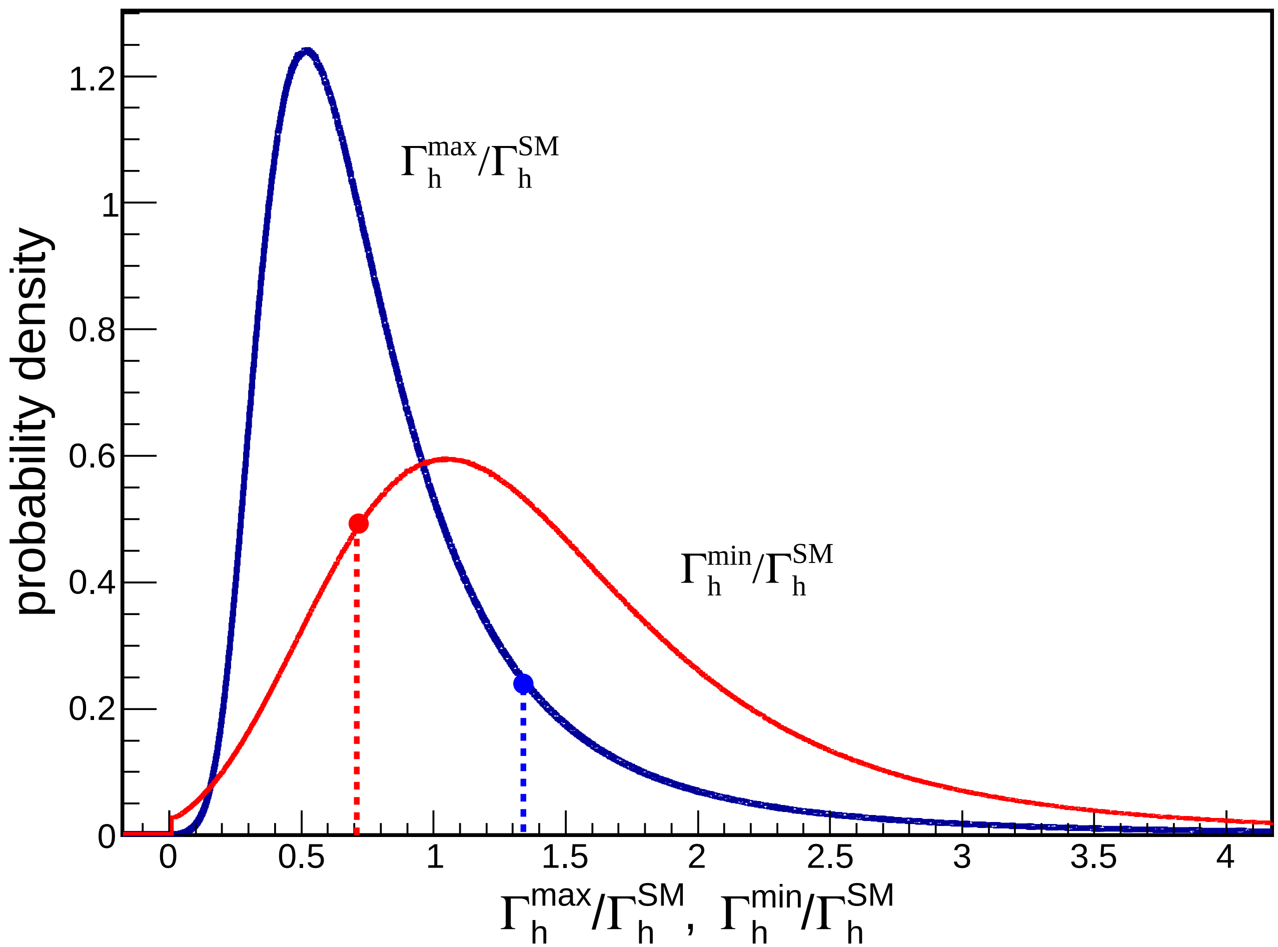
A lower limit on the Higgs width follows from the LHC and Tevatron rates required for observation.

An upper limit on Γ_h follows from the well-motivated assumption that the Higgs coupling to a W or Z pair is not much larger than in the Standard Model.

This range for Γ_h allows the extraction of a "span" (*i.e.*, lower and upper limits) for each Higgs coupling.

The upper limit for Γ_h implies an upper limit on the branching fraction of exotic Higgs decays. *(41% at the 95% CL, if the electroweak symmetry is broken only by doublets).*

Back-up slides

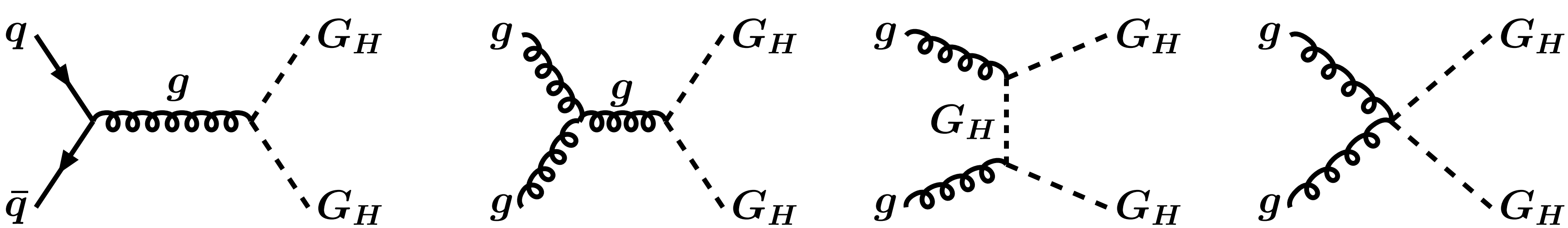


probability density
1.2
1
0.8
0.6
0.4
0.2
0
0.5
1.5
2
2.5
3
3.5
4
$\Gamma_h^{max}/\Gamma_h^{SM}$
$\Gamma_h^{min}/\Gamma_h^{SM}$
$\Gamma_h^{max}/\Gamma_h^{SM}$, $\Gamma_h^{min}/\Gamma_h^{SM}$

Scalar octet

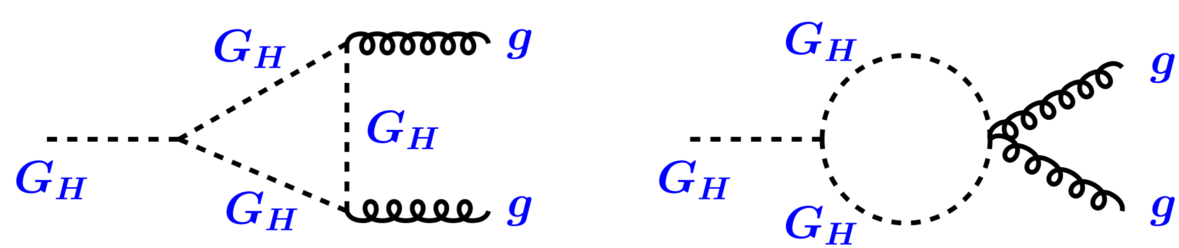
G_H: spin 0, transforms as (8,1,0) under $SU(3)_c \times SU(2)_W \times U(1)_Y$

$SU(2)_W$ forbids renormalizable couplings of G_H to SM quarks
$\Rightarrow$ production of G_H at hadron colliders occurs in pairs.

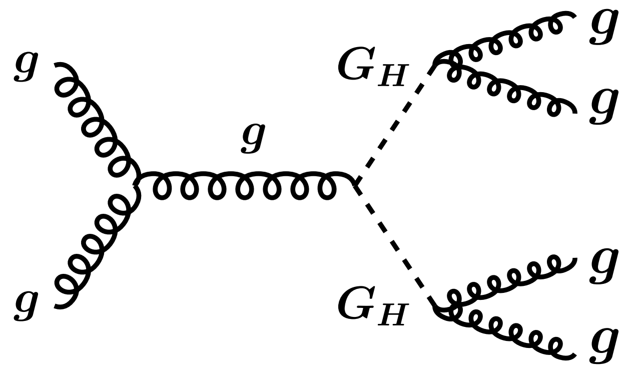


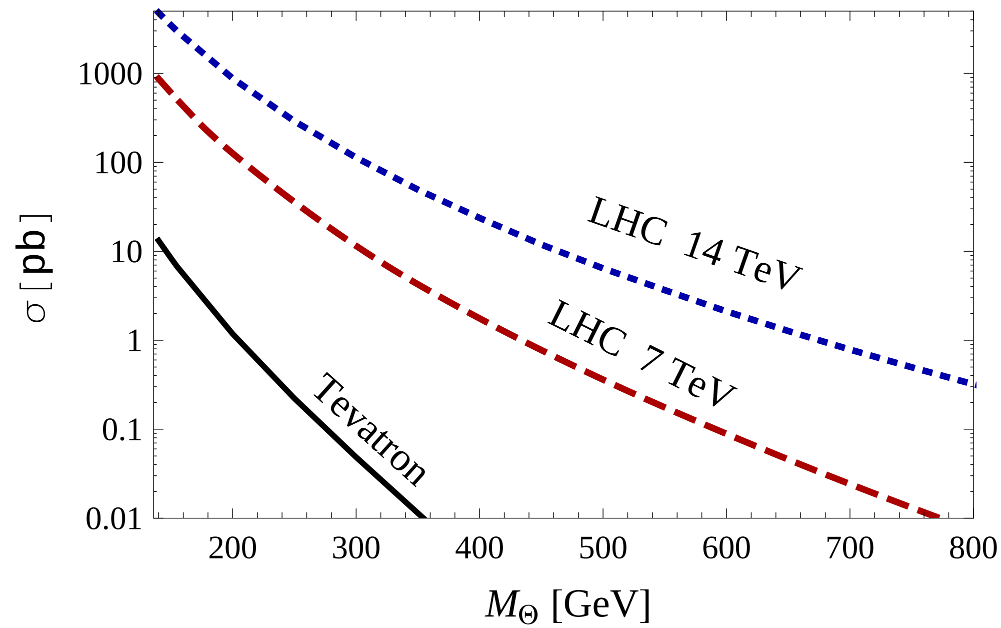
Invariance under $G_H \to -G_H$ violated by: $\mu\, d_{abc}\, G_H^a G_H^b G_H^c$

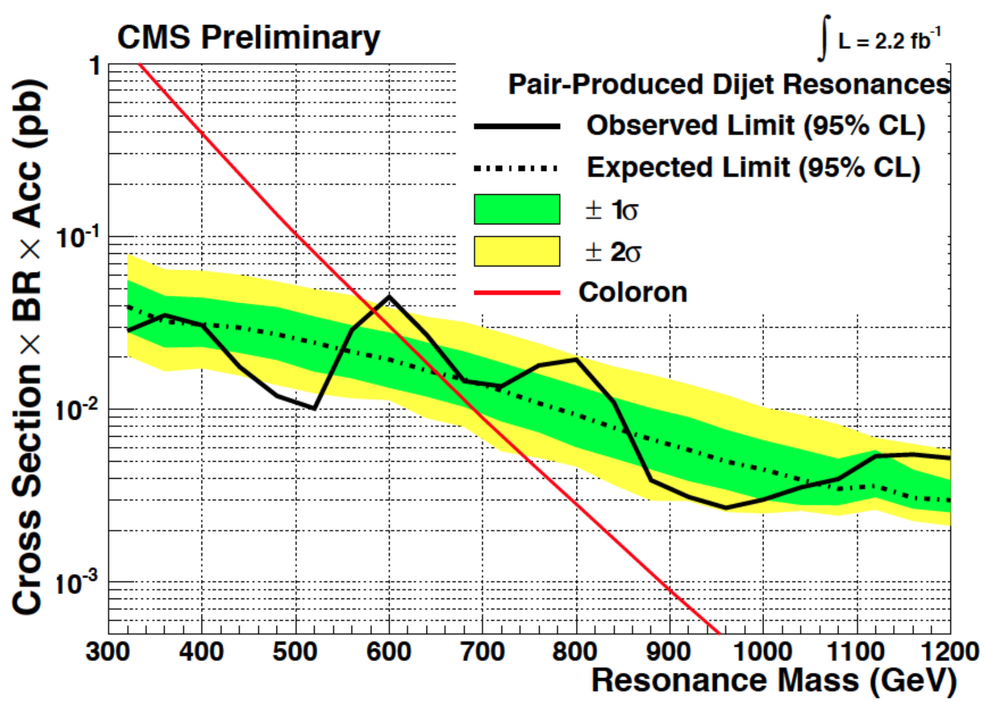
$G_H \to gg$ decay:

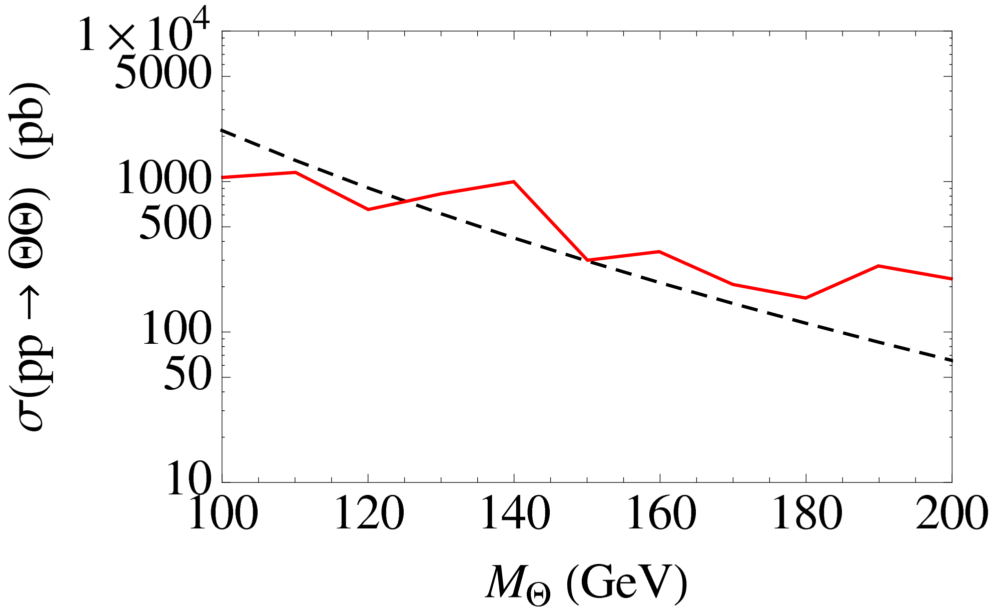


Signal: a pair of narrow gg resonances of same mass









ATLAS search for $(jj)(jj)$ (2010 data)

Before HCP:

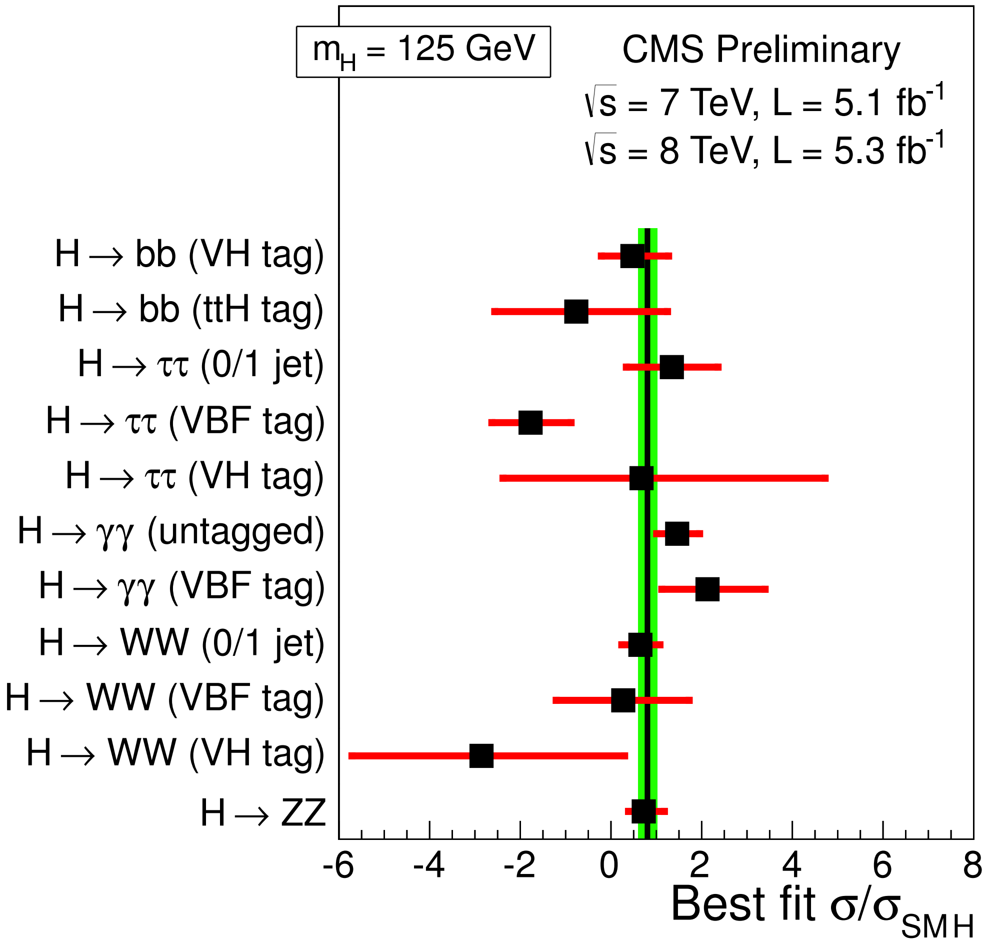
h^0 decay	h^0 production	observable	measured $\sigma/\sigma_{\rm SM}$; $M_h = 125$ GeV
WW^*	$gg \to h^0$	$a_g a_W$	1.3 ± 0.5, ATLAS ; 126 GeV $0.6^{+0.5}_{-0.4}$, CMS ; 125.5 GeV $0.3^{+0.8}_{-0.3}$, Tevatron our average: 0.9 ± 0.4
	VBF	$(a_W + r a_Z)/(1+r)\, a_W$	$0.3^{+1.5}_{-1.6}$, CMS
	$W^* \to W h^0$	a_W^2	$-2.9^{+3.2}_{-2.9}$, CMS
	$Z^* \to Z h^0$	$a_Z a_W$	
ZZ^*	$gg \to h^0$	$a_g a_Z$	$1.3^{+0.7}_{-0.5}$, ATLAS $0.7^{+0.5}_{-0.4}$, CMS ; 125.5 GeV our average: $1.0^{+0.4}_{-0.3}$
	VBF	$(a_W + r a_Z)/(1+r)\, a_Z$	
$\gamma\gamma$	$gg \to h^0$	$a_g a_\gamma$	1.7 ± 0.6 , ATLAS ; 126.5 GeV 1.4 ± 0.6 , CMS $3.6^{+3.0}_{-2.5}$, Tevatron our average: 1.6 ± 0.4
	VBF	$(a_W + r a_Z)/(1+r)\, a_\gamma$	2.6 ± 1.3 , ATLAS ; 126.5 GeV $2.1^{+1.4}_{-1.1}$, CMS our average: $2.3^{+1.0}_{-0.9}$

Before HCP:

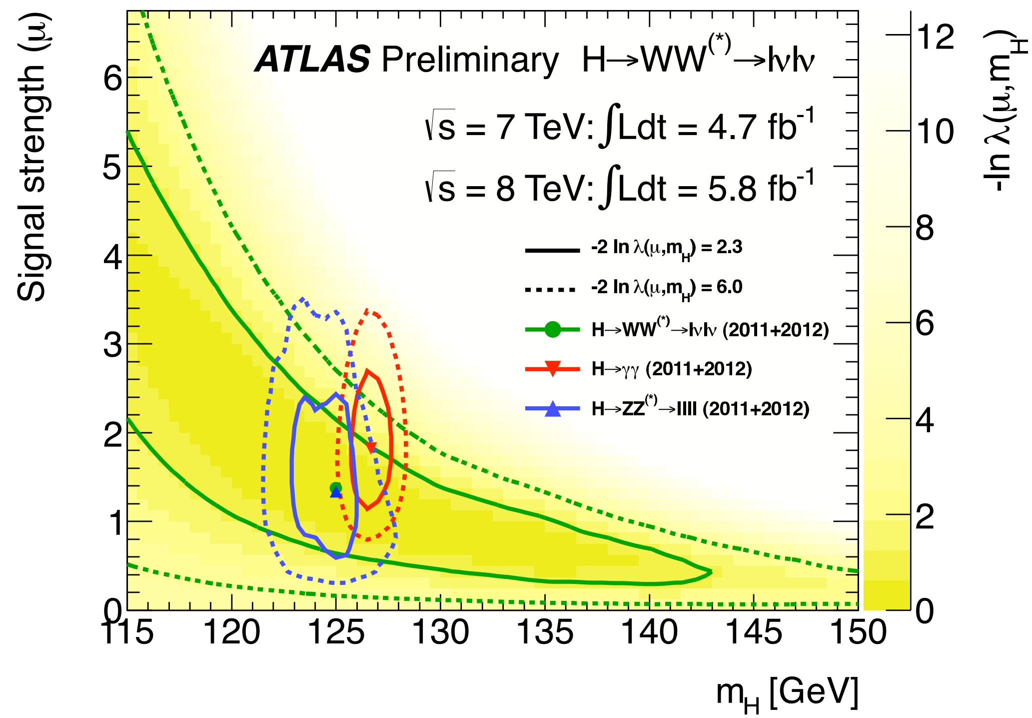
h^0 decay	h^0 production	observable	measured $\sigma/\sigma_{\rm SM}$; $M_h = 125$ GeV
$b\bar{b}$	$W^* \to W h^0$	$a_W a_b$	0.5 ± 2.2 , ATLAS ; 126 GeV $0.5^{+0.9}_{-0.8}$, CMS 2.0 ± 0.7, Tevatron our average: 1.4 ± 0.6
	$Z^* \to Z h^0$	$a_Z a_b$	
	$t\bar{t}h^0$	$a_t a_b$	$-0.8^{+2.1}_{-1.9}$, CMS
$\tau^+\tau^-$	$gg \to h^0$	$a_g a_\tau$	$0.4^{+1.6}_{-2.0}$, ATLAS ; 126 GeV 1.3 ± 1.1 , CMS our average: 1.0 ± 0.9
	VBF	$(a_W + r a_Z)/(1+r)\, a_\tau$	$-1.8^{+1.0}_{-0.9}$, CMS
	$W^* \to W h^0$	$a_W a_\tau$	$0.7^{+4.1}_{-3.2}$, CMS

Lower limit on the width:

$$\Gamma_h \geq \Gamma_h^{\rm min} = 1.05^{+1.26}_{-0.34}\, \Gamma_h^{\rm SM}$$



m_H = 125 GeV
CMS Preliminary
√s = 7 TeV, L = 5.1 fb^-1
√s = 8 TeV, L = 5.3 fb^-1
H → bb (VH tag)
H → bb (ttH tag)
H → ττ (0/1 jet)
H → ττ (VBF tag)
H → ττ (VH tag)
H → γγ (untagged)
H → γγ (VBF tag)
H → WW (0/1 jet)
H → WW (VBF tag)
H → WW (VH tag)
H → ZZ
-6 -4 -2 0 2 4 6 8
Best fit σ/σ_SM H



ATLAS Preliminary H→WW^(*)→lνlν
√s = 7 TeV: ∫Ldt = 4.7 fb^-1
√s = 8 TeV: ∫Ldt = 5.8 fb^-1
-2 ln λ(μ,m_H) = 2.3
-2 ln λ(μ,m_H) = 6.0
H→WW^(*)→lνlν (2011+2012)
H→γγ (2011+2012)
H→ZZ^(*)→llll (2011+2012)
Signal strength (μ)
0 1 2 3 4 5 6
115 120 125 130 135 140 145 150
m_H [GeV]
0 2 4 6 8 10 12
-ln λ(μ,m_H)