Interactions of the Higgs-like particle

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Work with Joe Lykken: *1210.3342*

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

Joint Theoretical-Experimental Seminar, Fermilab, 2013

Electroweak symmetry


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Sheldon Glashow

"Partial-symmetries of weak interactions" 1961

Weak & electromagnetic interactions described by

$SU(2)_W \times U(1)_Y$ gauge symmetry:

4 gauge bosons → $W^\pm$, Z^0, γ

If the laws of physics are gauge invariant,

where are the $W^\pm$ and Z^0 masses coming from?

Steven Weinberg

"A Theory of Leptons"

1967

Vacuum = ground state of a quantum field theory.

Lagrangian has $SU(2)_W \times U(1)_Y$ gauge symmetry,

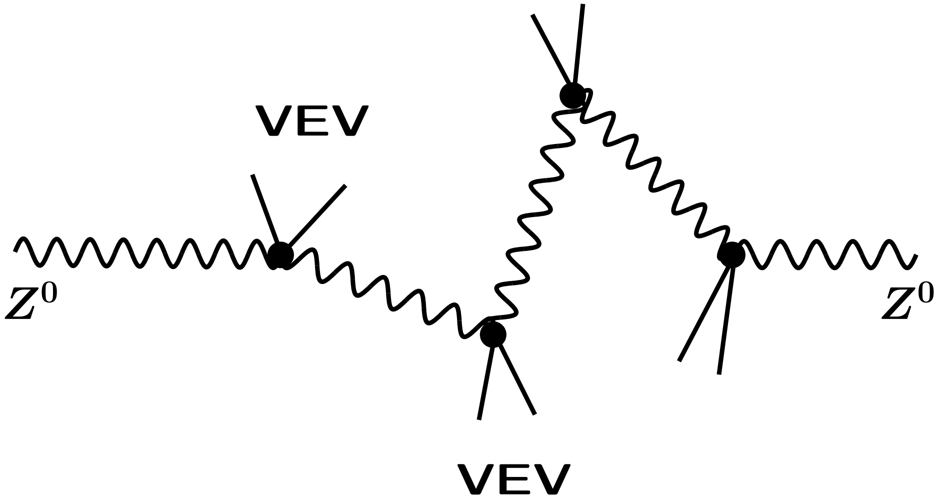
vacuum has only $U(1)_{\mathrm{e.m.}}$ gauge symmetry.

Similar to superconductivity: photon is massive inside superconductors.

Need something to populate the vacuum ...

Higgs field 'condenses', has a Vacuum Expectation Value:

$$v = (2/g)M_W \approx 246 \text{ GeV}$$



Z^0 acquires a mass!

Within the Standard Model, the Higgs field is an $SU(2)_W$ doublet:

$$H = \begin{pmatrix} W_L^+ \\ \frac{1}{\sqrt{2}}\left(v + h^0 + iZ_L\right) \end{pmatrix}$$

(W_L is the longitudinally-polarized W boson)

SM Higgs field implies the existence of a particle h^0 carrying the same quantum numbers as the vacuum.

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

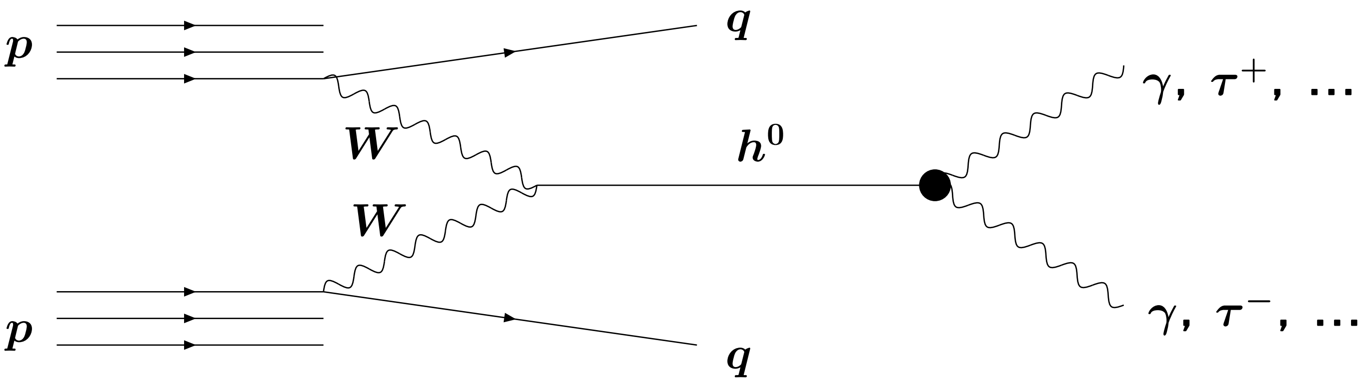
$$\frac{g}{M_W} h^0 \left(C_W M_W^2 W_\mu^+ W^{-\mu} + C_Z \frac{M_Z^2}{2} Z_\mu Z^\mu \right)$$

$g \approx 0.6$ is the $SU(2)_W$ gauge coupling.

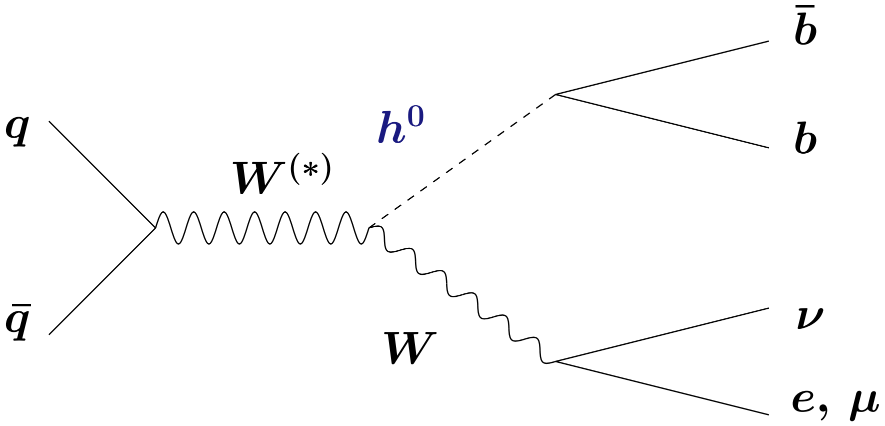
C_W and C_Z parametrize the deviation from the SM couplings:

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

The LHC is not only a quark-quark or a gluon-gluon collider, but also a $\boldsymbol{WW}$ and a $\boldsymbol{ZZ}$ collider!



Higgs boson can also be radiated by a W or Z boson:



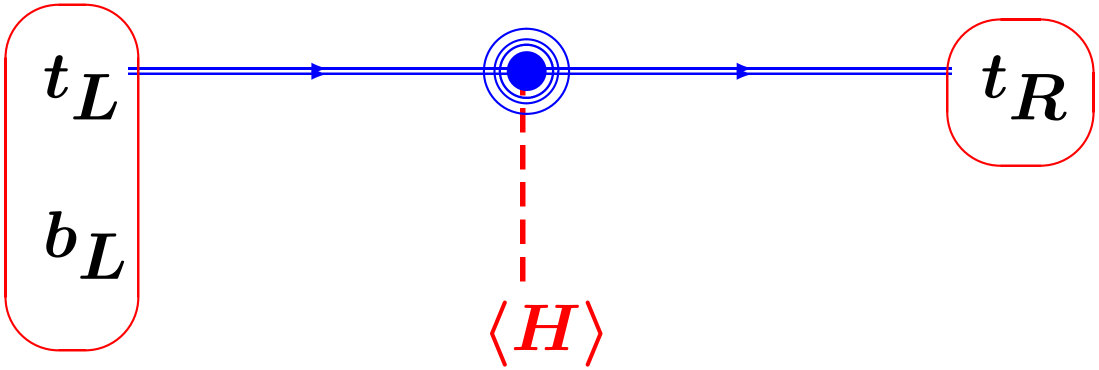
3σ observation at the Tevatron

Chiral quarks

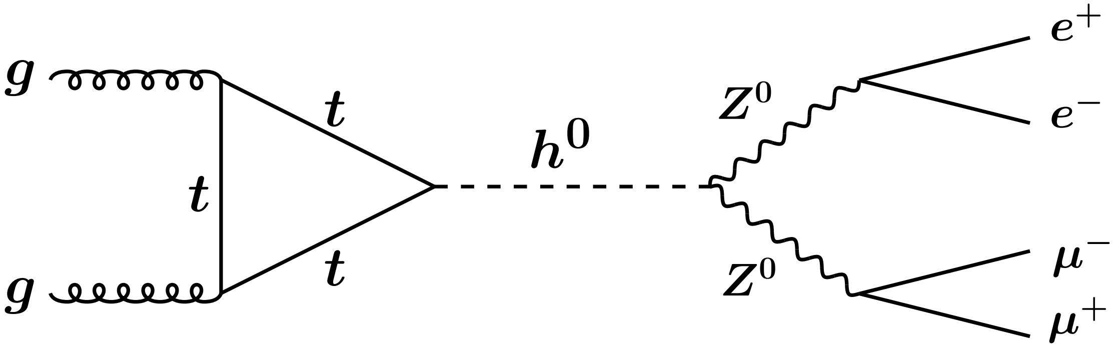
The two top quarks:

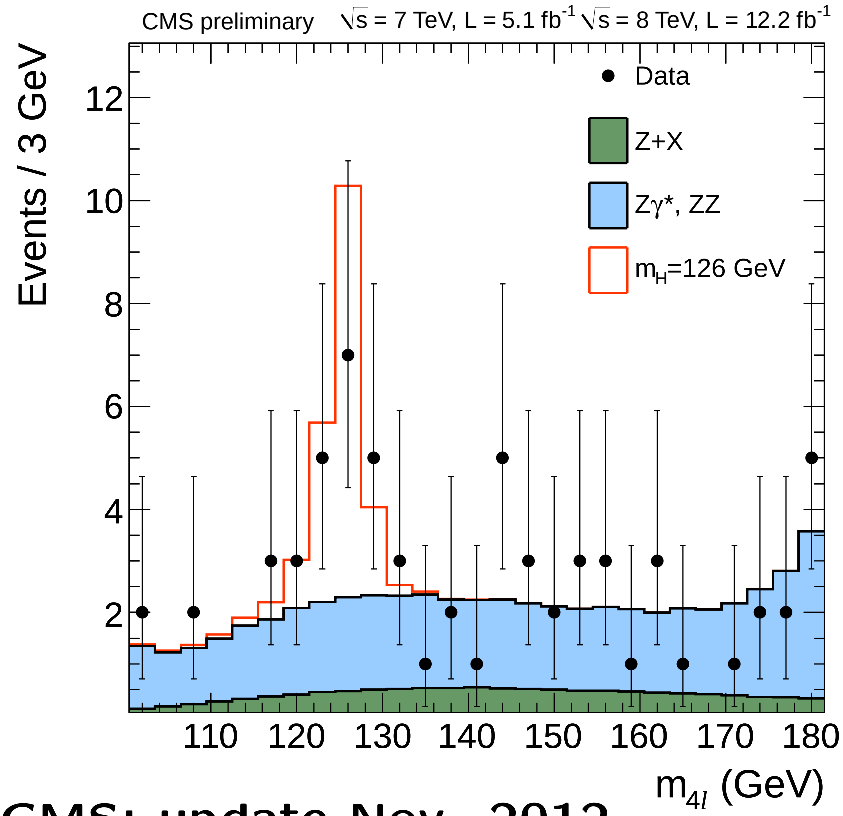
- “left-handed” top – *part of an* $SU(2)_W$ *doublet*
- “right-handed” top – $SU(2)_W$ *singlet*

Top mass: t_L turns into t_R and vice-versa

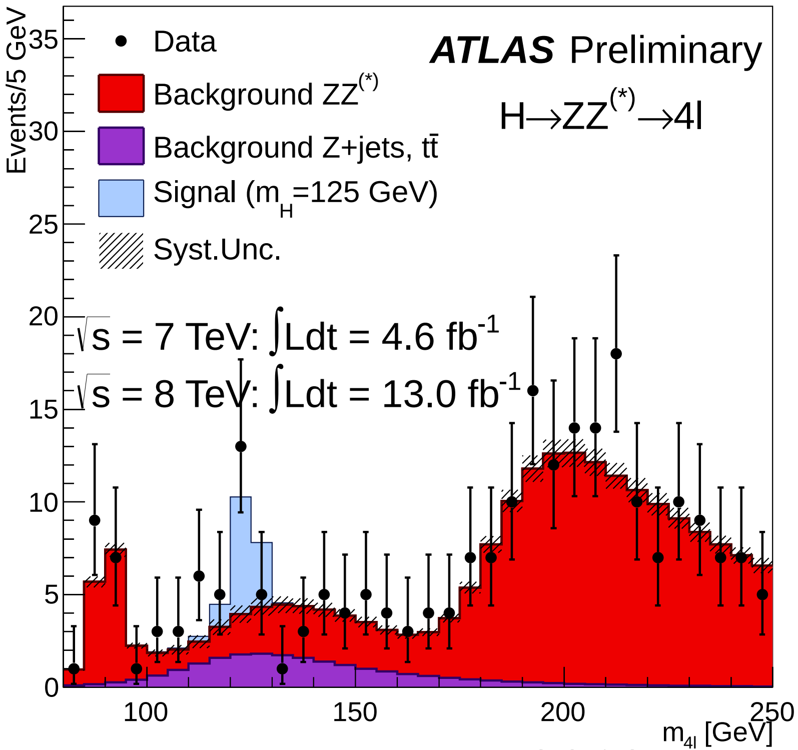


Large coupling of h^0 to the top quark implies that the Higgs boson is copiously produced in gluon fusion at the LHC:





CMS: update Nov. 2012



ATLAS: update Dec 2012

Couplings of a Higgs boson to 3rd generation fermions:

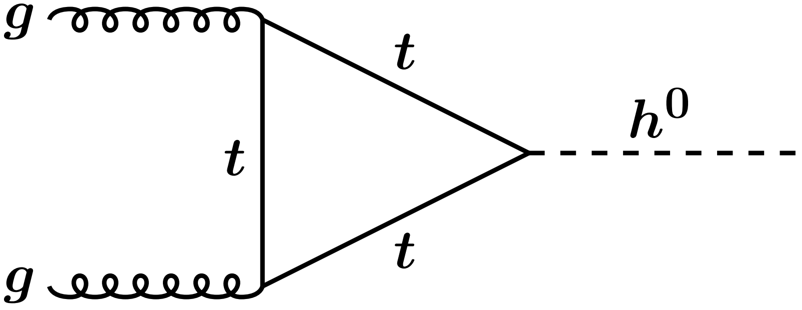
$$-C_t \frac{m_t}{v} h^0 \, \bar{t} t - C_b \frac{m_b}{v} h^0 \, \bar{b} b - C_\tau \frac{m_\tau}{v} h^0 \, \bar{\tau} \tau$$

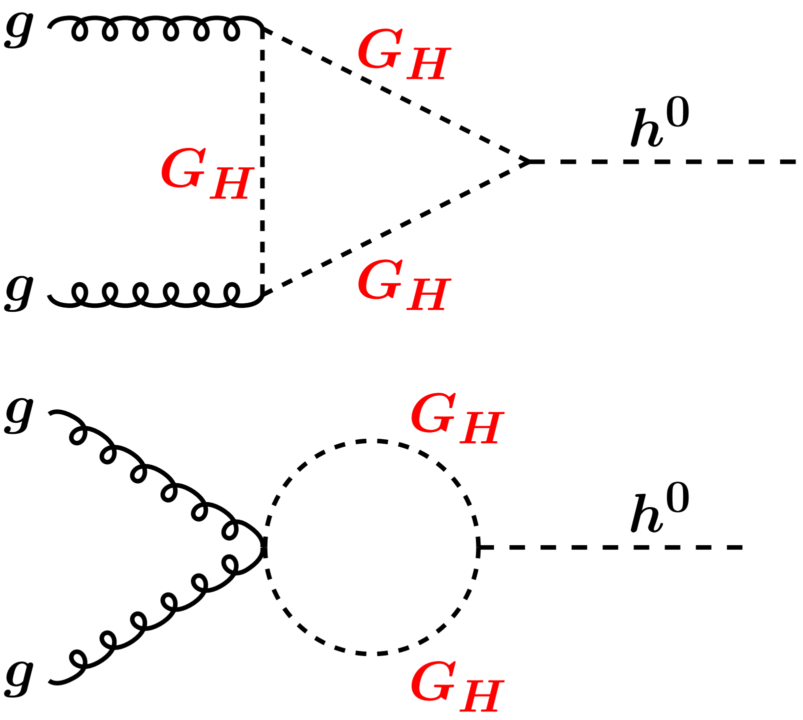
C_t, C_b, C_τ are real parameters, equal to 1 in the SM.

Extensions of the SM with two or more Higgs doublets allow C_b and C_τ to be orders of magnitude larger or smaller than 1, while $C_t \lesssim O(1)$.

Non-standard Higgs production

Standard-Model gluon fusion ± non-standard contributions





Higgs 'portal' coupling: $\kappa\, G_H^a G_H^a H^\dagger H$, G_H **has spin 0, carries color.**

The direct signatures of the new colored particles at the LHC may have large backgrounds.

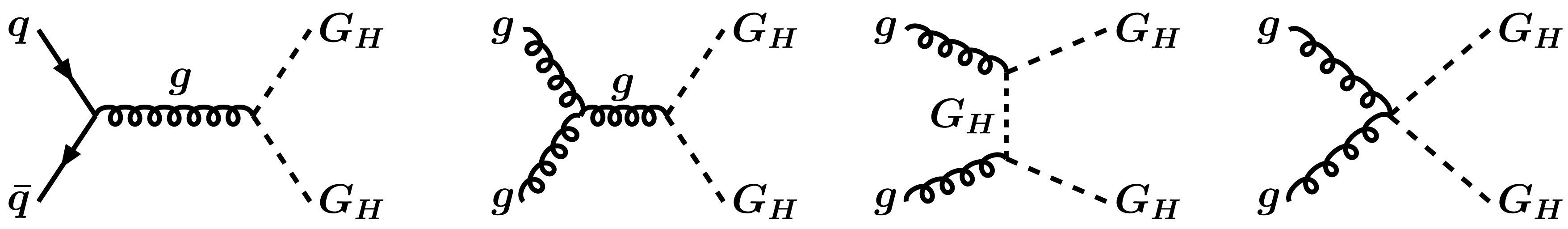
Scalar octet

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.

Renormalizable couplings of G_H to gluons are fixed by $SU(3)_c$ gauge invariance

$\Rightarrow$ production of G_H at hadron colliders occurs in pairs.

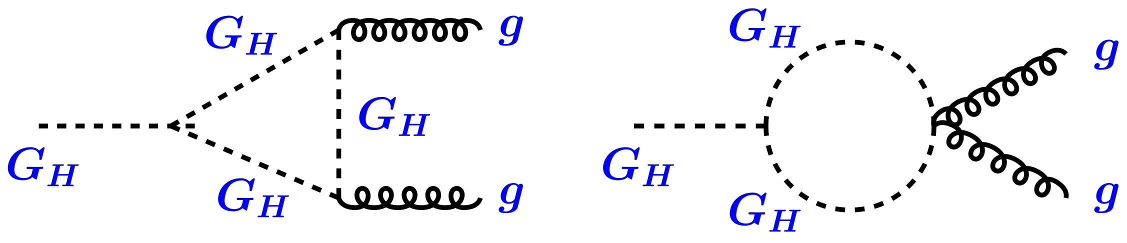


Dobrescu, Kong, Mahbubani, hep-ph/0709.2378

G_H decays are model dependent.

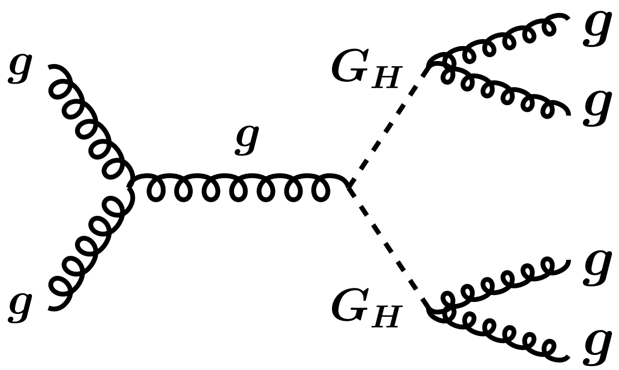
A simple possibility: $G_H \to gg$

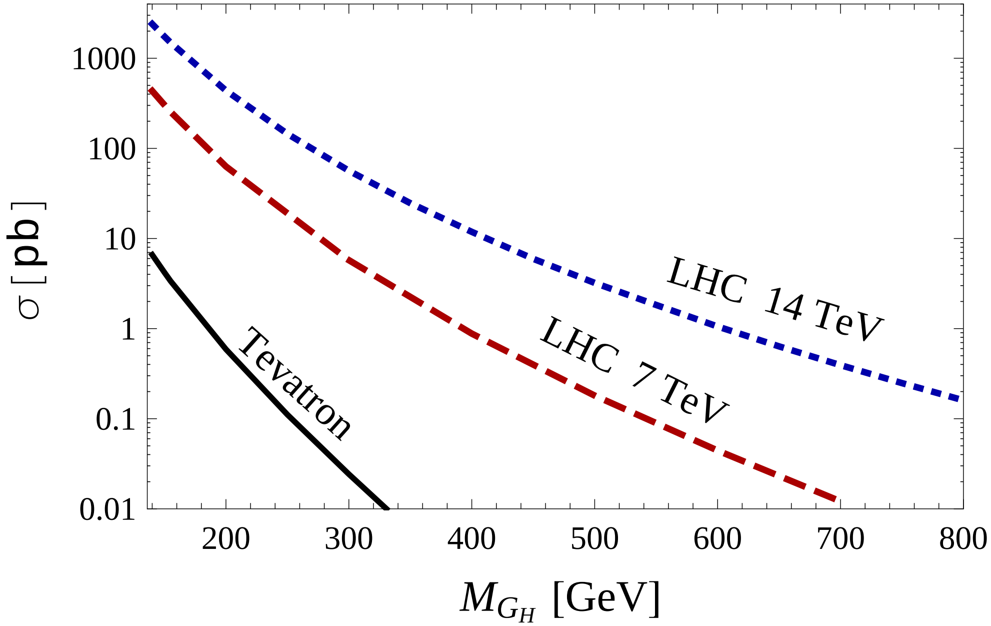
Dobrescu, Bai, 1012.5814

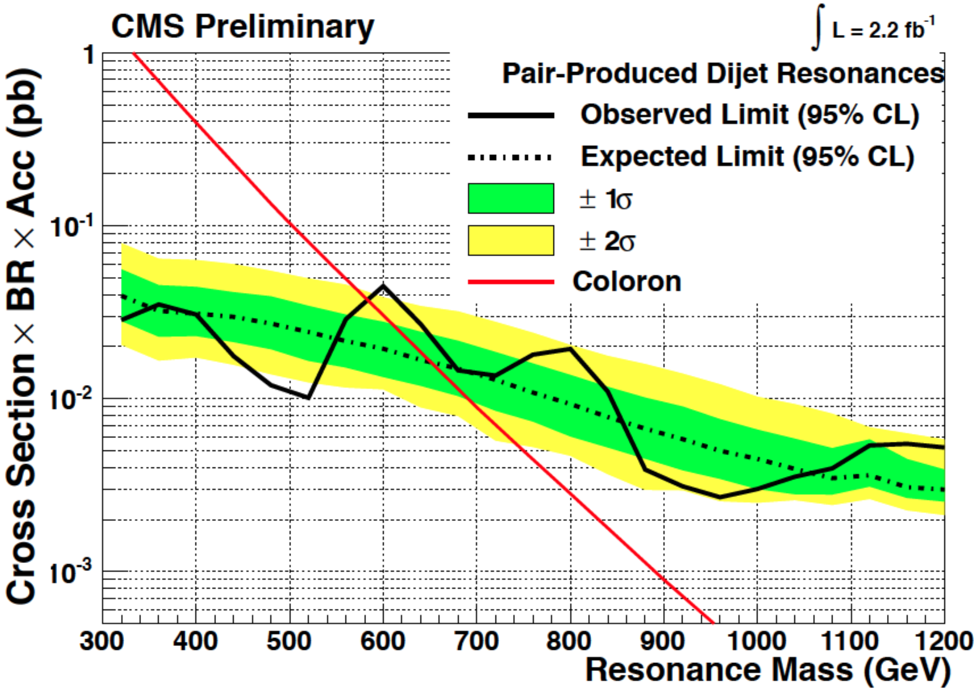


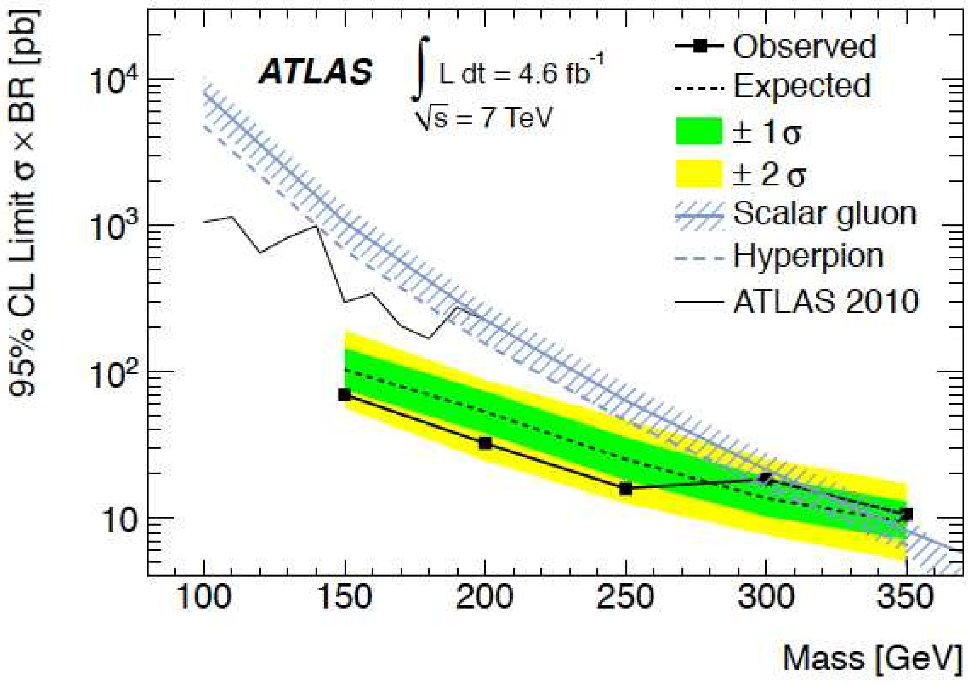
A more complicated decay: $G_H \to \bar{\psi}^* \psi^* \to g\bar{q}\, gq$

Signal: a pair of narrow gg resonances of same mass









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

Effective 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:

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

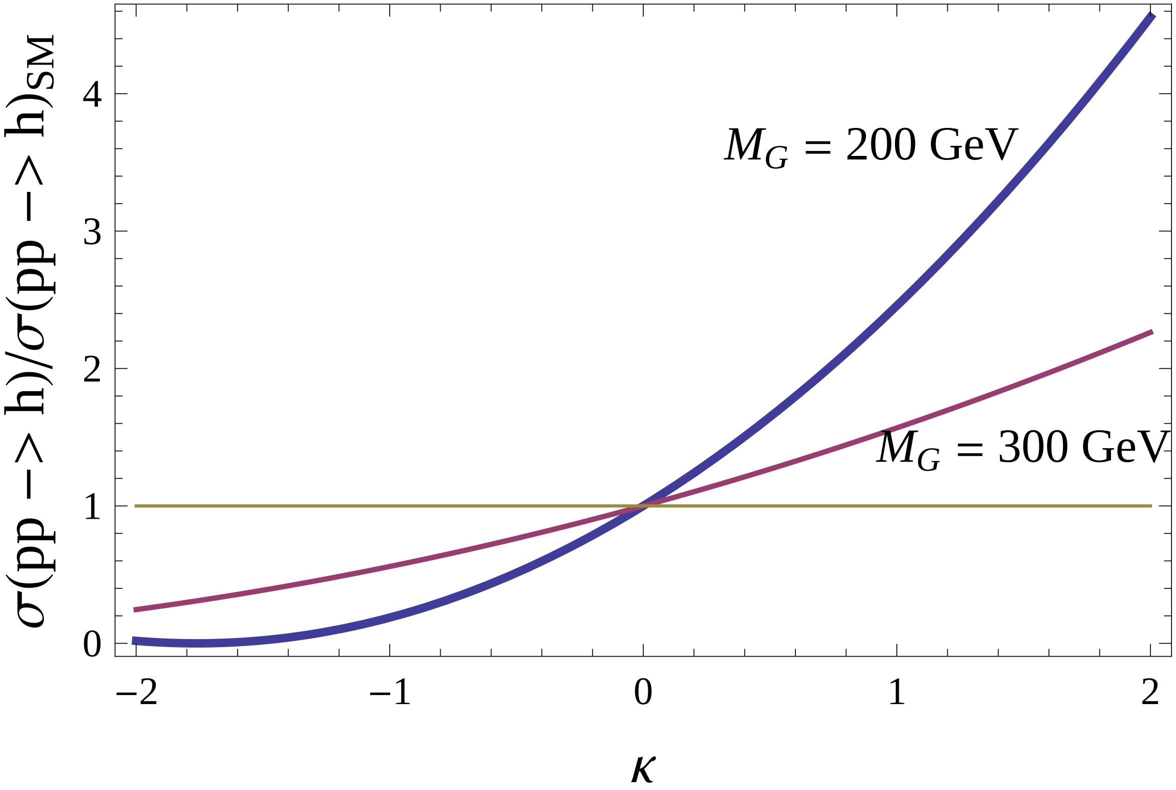
Within the SM: $C_g = C_\gamma = 1$. *Deviations from 1 are due to new particles in the loops as well as changes in the Higgs couplings to* $\bar{t}t$ *and* WW.

Couplings of a non-standard Higgs boson are described by 7 parameters: $C_W, C_Z,\ C_t, C_b, C_\tau,\ C_g, C_\gamma$.

Eventually, $C_{Z\gamma}$ **and** C_μ **will also be important** **(also** $h \to \tau\mu$**, ...**
Harnik et al, 1209.1397)

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

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)

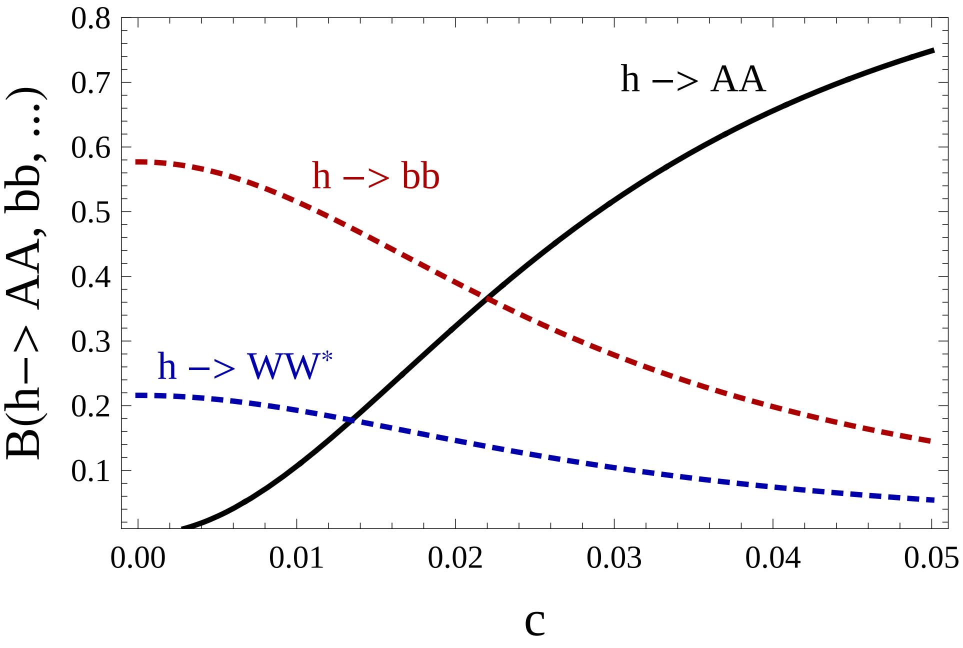
Nonstandard Higgs decays

Standard model + a gauge-singlet complex scalar S:

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

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

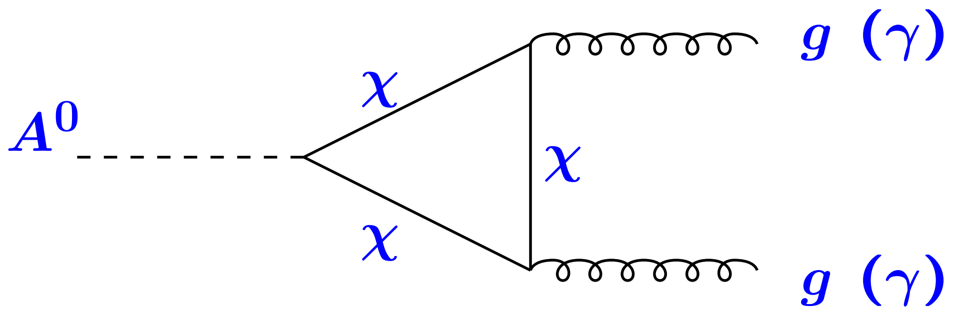
For $2M_A \ll M_h = 125$ GeV:



Higgs boson may be the portal to a hidden sector: dark matter, ...

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 ...)*

Importance of the total width

Cross section × branching fractions:

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

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

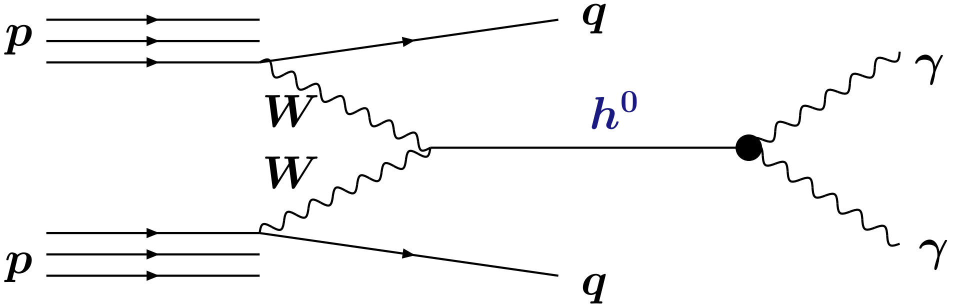
Duhrssen, et al, hep-ph/0407190
Barger, Ishida, Keung, 1203.3456
HXSWG, 1209.0040, ...

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

How can we extract the Higgs couplings?

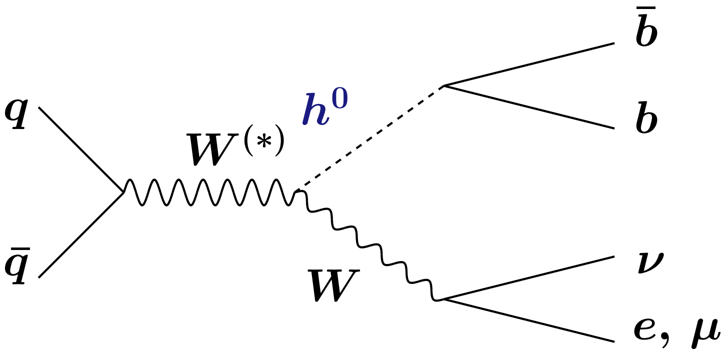
E.g., an increase in all couplings can be compensated by a larger Γ_h *due to (almost) undetectable decays through new particles.*

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

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

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

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

where $a_W = a_Z \equiv a_V$.

h^0 decay	h^0 production	observable	measured $\sigma/\sigma_{\rm SM}$
WW^*	$gg \to h^0$	$a_g a_W$	$1.35^{+0.57}_{-0.55}$, ATLAS $0.77^{+0.27}_{-0.25}$, CMS $0.8^{+0.9}_{-0.8}$, Tevatron our average: $0.88^{+0.24}_{-0.23}$
	VBF	$(a_W + r a_Z)/(1+r)\, a_W$	$-0.05^{+0.74}_{-0.55}$, CMS
	$W^* \to W h^0$	a_W^2	$-0.31^{+2.22}_{-1.94}$, CMS
	$Z^* \to Z h^0$	$a_Z a_W$	
ZZ^*	$gg \to h^0$	$a_g a_Z$	$1.07^{+0.5}_{-0.4}$, ATLAS $0.80^{+0.35}_{-0.28}$, CMS our average: $0.90^{+0.28}_{-0.24}$
	VBF	$(a_W + r a_Z)/(1+r)\, a_Z$	
$\gamma\gamma$	$gg \to h^0$	$a_g a_\gamma$	1.8 ± 0.5 , ATLAS 1.4 ± 0.6 , CMS $6.1^{+3.3}_{-3.2}$, Tevatron our average: 1.7 ± 0.4
	VBF	$(a_W + r a_Z)/(1+r)\, a_\gamma$	2.0 ± 1.4 , ATLAS $2.1^{+1.4}_{-1.1}$, CMS our average: $2.1^{+1.0}_{-0.9}$
	$W^* \to W h^0$	$a_W a_\gamma$	1.9 ± 2.6 , ATLAS
	$Z^* \to Z h^0$	$a_Z a_\gamma$	

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,

$$a_V = 1.05^{+0.30}_{-0.29}$$

This implies:

$$\Gamma_h \leq \Gamma_h^{\rm max} = 0.65^{+1.06}_{-0.10}\, \Gamma_h^{\rm SM}$$

Lower limit on Γ_h

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

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

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

Given that $\Gamma_X \geq 0$,

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

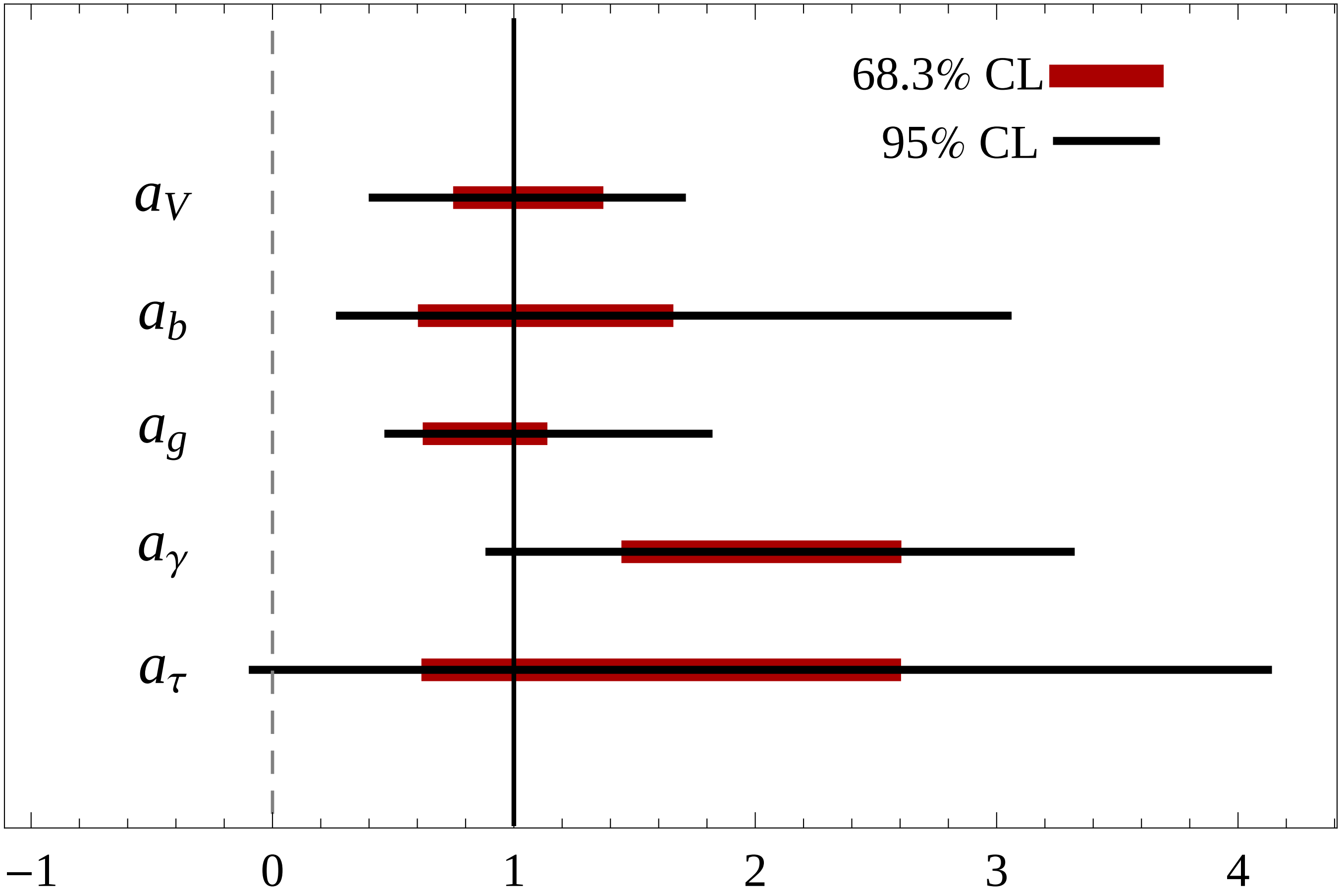
h^0 decay	h^0 production	observable	measured $\sigma/\sigma_{\rm SM}$
$b\bar{b}$	$W^* \to W h^0$	$a_W a_b$	-0.3 ± 1.0 , ATLAS $1.31^{+0.65}_{-0.60}$, CMS $1.56^{+0.72}_{-0.73}$, Tevatron our average: 1.1 ± 0.4
	$Z^* \to Z h^0$	$a_Z a_b$	
	$t\bar{t}h^0$	$a_t a_b$	$-0.80^{+2.10}_{-1.84}$, CMS
$\tau^+\tau^-$	$gg \to h^0$	$a_g a_\tau$	2.4 ± 1.7 , 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 ± 1.2 , 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:

$$\Gamma_h \geq \Gamma_h^{\rm min} = 0.97^{+0.83}_{-0.27}\, \Gamma_h^{\rm SM}$$

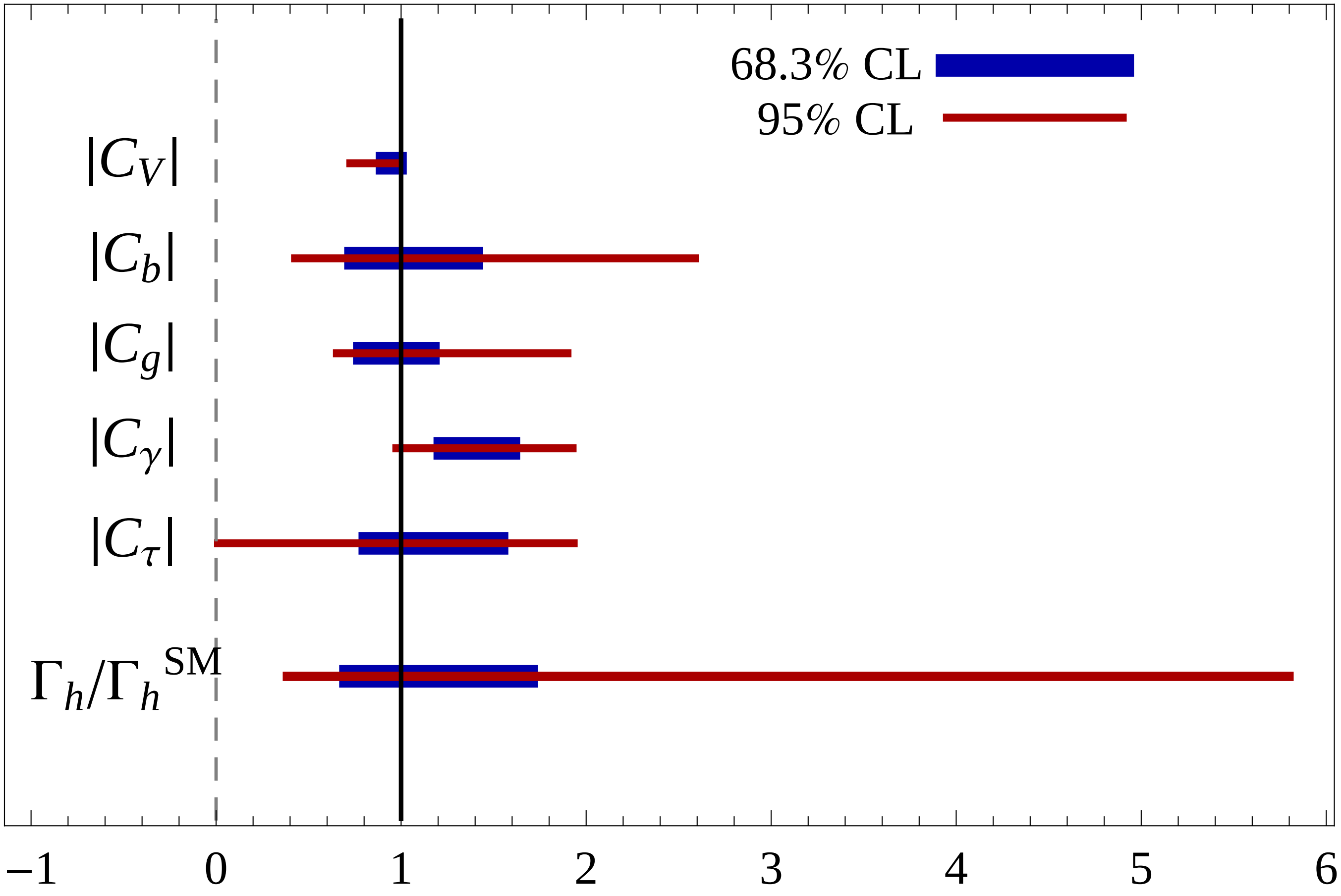
$$a_{\mathcal{P}} = C_{\mathcal{P}}^2 \left(\frac{\Gamma_h^{\text{SM}}}{\Gamma_h} \right)^{1/2}$$

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’:



updated in Jan 2013, based on Dobrescu, Lykken: 1210.3342

Branching fraction of exotic decays:

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

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

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

$\mathcal{B}_X^{\rm max} < 22\%$ at the 68% CL

$\mathcal{B}_X^{\rm max} < 52\%$ at the 95% CL.

Vectorlike quarks

All Standard Model fermions are chiral: their masses arise from the Higgs coupling.

Vectorlike (*i.e.* non-chiral) elementary fermions

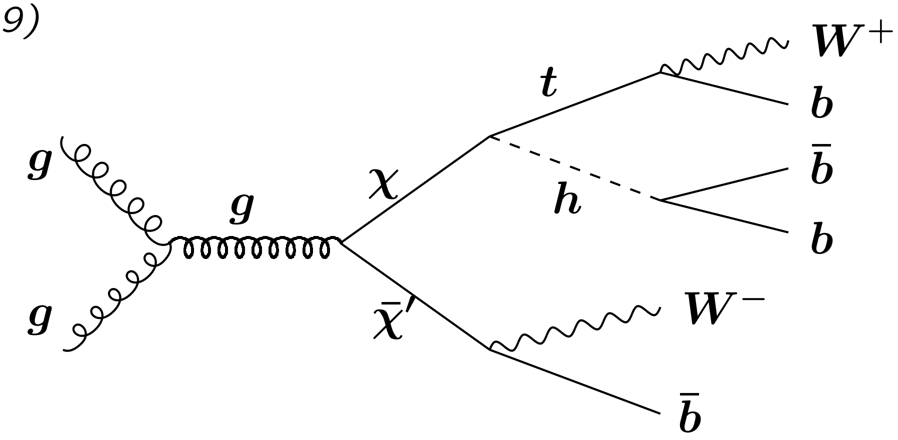
– a new (hypothetical) form of matter.

Masses allowed by $SU(2)_W \times U(1)_Y$ gauge symmetry

⇒ naturally heavier than the t quark.

A vectorlike quark χ which mixes with the top quark:

(B. Dobrescu, KC Kong, R. Mahbubani, 2009)

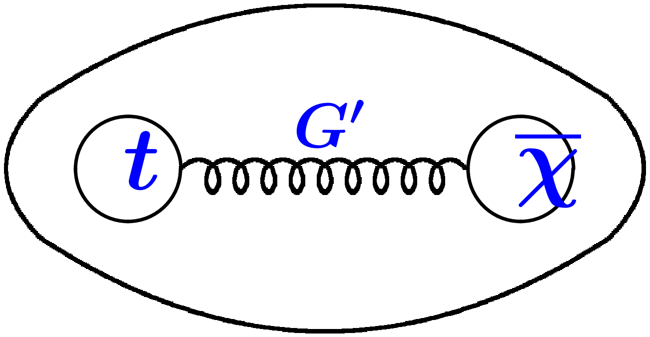


Higgs boson may lead to the discovery of the vectorlike quark.

Is the Higgs boson an elementary particle or a bound state ?

Composite Higgs field as a bound state of the top quark and a vectorlike quark *(S. Chivukula, B. Dobrescu, H. Georgi, C. Hill, 1998)*

Binding due to some new strongly coupled interaction:



Conclusions

Higgs boson is a sensitive probe of various phenomena beyond the Standard Model.

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. *(52% at the 95% CL, if the electroweak symmetry is broken only by doublets).*