Couplings and width of the Higgs (-like) particle

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Work with Joe Lykken: *1210.3342*

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

Theory Seminar - UC Davis, April 15, 2013

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

$$\frac{h^0}{v_h}\left(2\kappa_W M_W^2 W_\mu^+ W^{-\mu} + \kappa_Z M_Z^2 Z_\mu Z^\mu\right)$$

$v_h \approx 246$ **GeV**

Couplings of a Higgs boson to 3rd generation fermions:

$$-\frac{h^0}{v_h}\left(\kappa_t m_t \bar{t}t + \kappa_b m_b \bar{b}b + \kappa_\tau m_\tau \bar{\tau}\tau\right)$$

κ_W, κ_Z, $\kappa_t, \kappa_b, \kappa_\tau$ **are real parameters, equal to 1 in the SM.**

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

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

Effective coupling to photons:

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

Within the SM: $\kappa_g = \kappa_\gamma = 1$. *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: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_g, \kappa_\gamma$.

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

Importance of the total width

Cross section $\times$ branching fractions for $\Gamma_h \ll M_h$:

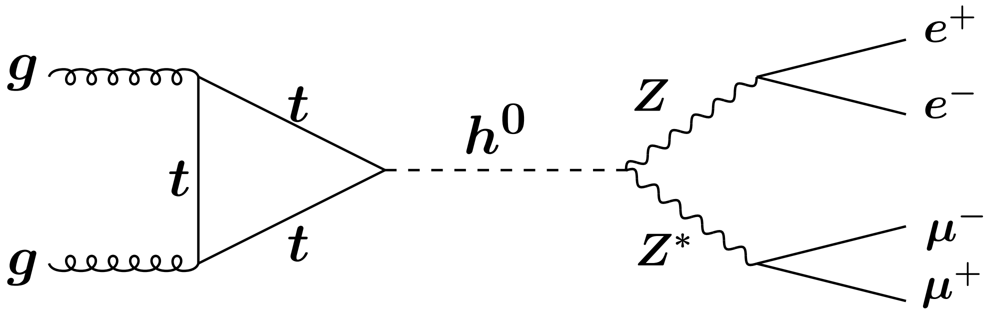
$$\sigma(pp \to h + X \to ... + X) \propto \frac{1}{\Gamma_h}$$

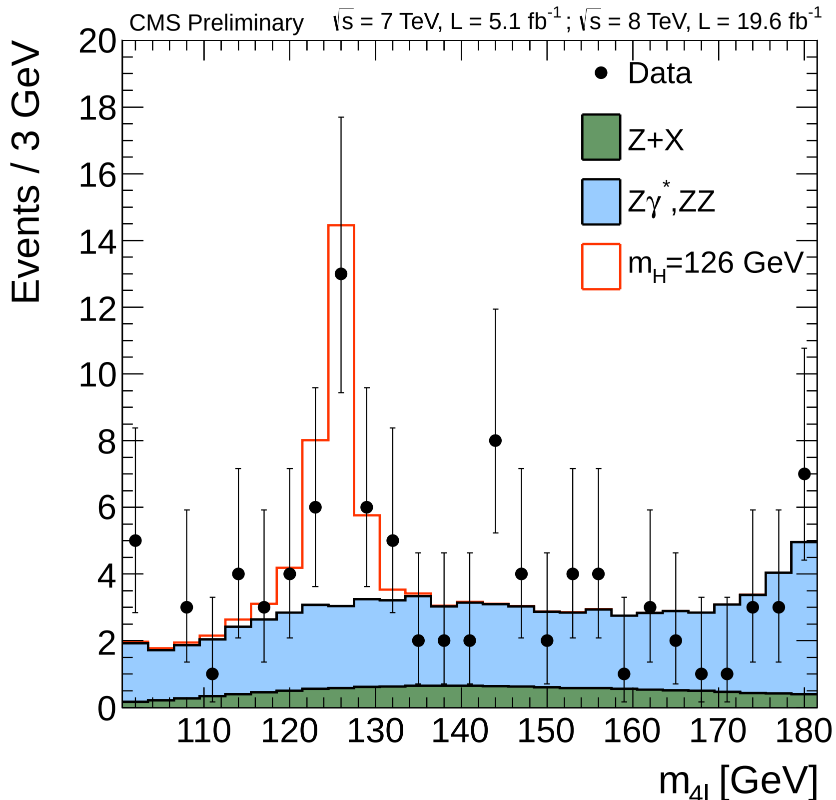
$\Gamma_h^{\rm SM}/M_h \approx 3.2 \times 10^{-5}$ **for** $M_h = 126$ **GeV.**

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

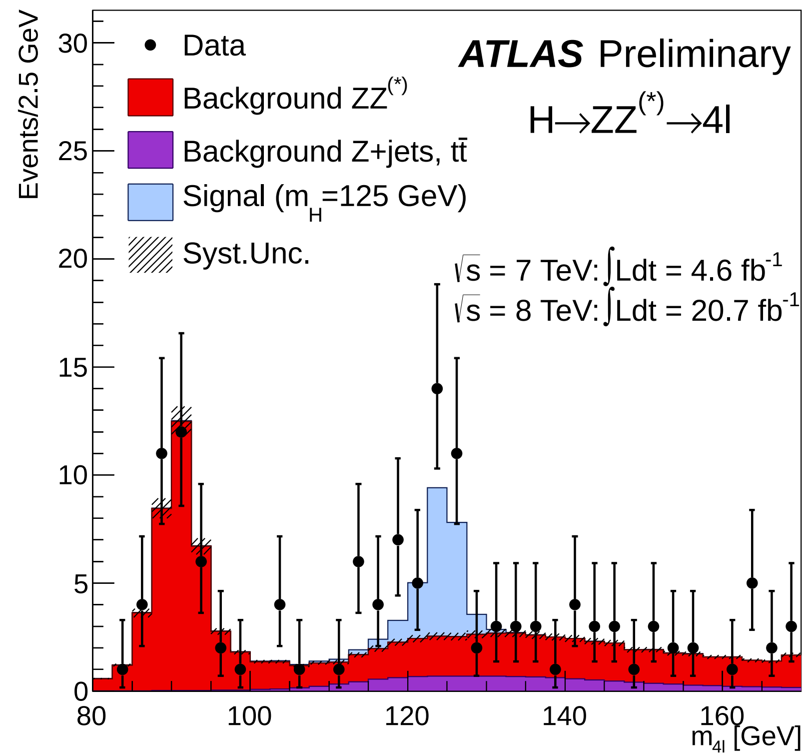
Duhrssen, et al, hep-ph/0407190
Barger, Ishida, Keung, 1203.3456
HXSWG, 1209.0040, ...

Higgs couplings $\kappa_{\mathcal{P}}$ cannot be extracted from LHC data,
in the absence of some theoretical assumptions, **because**
an increase in all couplings can be compensated by a larger Γ_h
due to (almost) undetectable decays through new particles.





CMS: $M_h = 125.8 \pm 0.5$ **GeV**



ATLAS: $M_h = 124.3 \pm 0.7$ **GeV**

Current resolution (~ 1 **GeV**) **implies** $$\frac{\Gamma_h}{\Gamma_h^{\rm SM}} \lesssim 10^2$$

Our method *(1210.3342)*:

1. Define the "apparent squared couplings":

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

$a_{\mathcal{P}}$ can be extracted directly from the CMS and ATLAS data:

$$\text{Rate} = a_{\rm prod.}\, a_{\rm decay}$$

2. Based on some theoretical assumption, the couplings $\kappa_{\mathcal{P}}$ (Lagrangian parameters!) can then be related to $a_{\mathcal{P}}$.

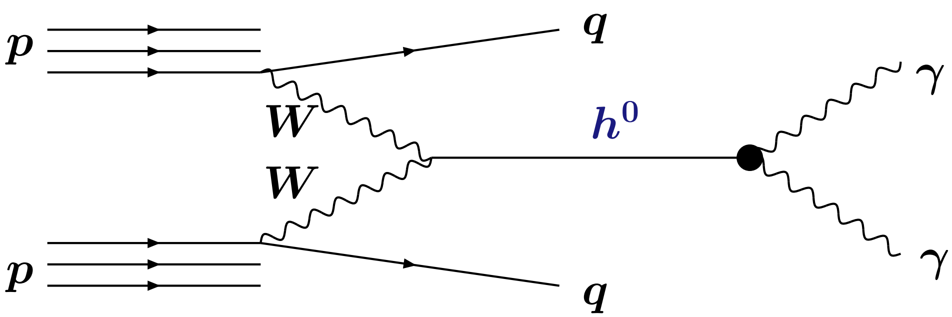
Assumptions used by CMS PAS-HIG-12-045 (Nov. 2012) ,

ATLAS-CONF-2012-127 (Sept. 2012), HXSWG (1209.0040):

no decays into non-SM particles, or some $\kappa_{\mathcal{P}} = 1$.

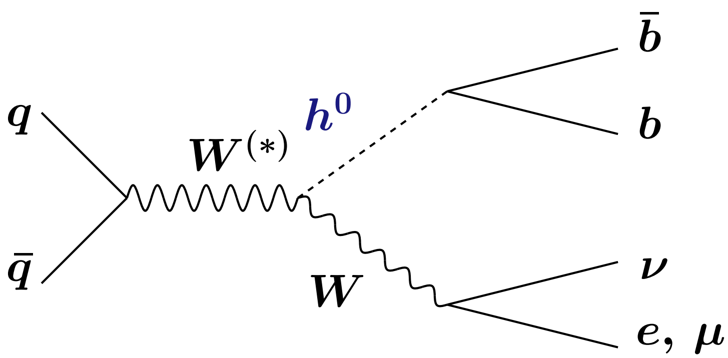
A well-motivated assumption: an upper limit on κ_W or κ_Z.

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



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

$r \approx 0.3$



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

...

Contamination of "VBF tagged" sample from the gluon fusion (+ jj) channel:

$$a_{\mathrm{VBF}} \approx (1 - f_g)\frac{a_W + r a_Z}{1 + r} + f_g a_g$$

SM simulations: $f_g \approx 30\%$ **(20% - 50% depending on event selection)**

Contamination of gluon fusion from VBF is small ($\sim 10\%$).

h^0 decay	h^0 production	observable	measured $\sigma/\sigma_{\rm SM}$
WW^*	$gg \to h^0$	$a_g a_W$	0.8 ± 0.4, ATLAS 0.76 ± 0.21 , CMS $0.94^{+0.85}_{-0.83}$, Tevatron our average: 0.78 ± 0.18
	VBF	$a_{\rm VBF}\, a_W$	1.7 ± 0.8, ATLAS $-0.05^{+0.74}_{-0.55}$, CMS
	$W^* \to Wh^0$	a_W^2	$-0.3^{+2.2}_{-1.9}$, CMS
	$Z^* \to Zh^0$	$a_Z a_W$	
ZZ^*	$gg \to h^0$	$a_g a_Z$	1.5 ± 0.4 , ATLAS $0.9^{+0.5}_{-0.4}$, CMS our average: 1.3 ± 0.3
	VBF	$a_{\rm VBF}\, a_Z$	$1.0^{+2.4}_{-2.3}$, CMS

h^0 decay	h^0 production	observable	measured $\sigma/\sigma_{\mathrm{SM}}$
$\gamma\gamma$	$gg \to h^0$	$a_g a_\gamma$	$1.6^{+0.5}_{-0.4}$, ATLAS $0.5^{+0.6}_{-0.4}$, CMS $6.0^{+3.4}_{-3.1}$, Tevatron our average: 1.4 ± 0.4
	VBF	$a_{\mathrm{VBF}}\, a_\gamma$	$1.7^{+1.0}_{-0.8}$, ATLAS 1.5 ± 1.1 , CMS our average: $1.6^{+0.7}_{-0.6}$
	$W^* \to W h^0$	$a_W a_\gamma$	1.8 ± 1.4 , ATLAS
	$Z^* \to Z h^0$	$a_Z a_\gamma$	

h^0 decay	h^0 production	observable	measured $\sigma/\sigma_{\rm SM}$
$b\bar{b}$	$W^* \to Wh^0$	$a_W a_b$	-0.4 ± 1.0 , ATLAS $1.31^{+0.65}_{-0.60}$, CMS $1.59^{+0.69}_{-0.72}$, Tevatron our average: 1.1 ± 0.4
	$Z^* \to Zh^0$	$a_Z a_b$	
	$t\bar{t}h^0$	$a_t a_b$	$-0.80^{+2.10}_{-1.84}$, CMS
$\tau^+\tau^-$	$gg \to h^0$	$a_g a_\tau$	2.4 ± 1.7 , ATLAS $0.8^{+0.5}_{-0.6}$, CMS $1.7^{+2.3}_{-1.7}$, Tevatron our average: $1.0^{+0.4}_{-0.5}$
	VBF	$a_{\rm VBF}\, a_\tau$	-0.4 ± 1.2 , ATLAS 1.4 ± 0.6 , CMS
	$W^* \to Wh^0$	$a_W a_\tau$	? , ATLAS 0.8 ± 1.5 , CMS
	$Z^* \to Zh^0$	$a_Z a_\tau$	

Electroweak data requires $\kappa_W/\kappa_Z = 1 \pm O(10^{-2})$
(unless some BSM contributions are tuned to cancel the effects of h^0)

For simplicity, assume $\kappa_W = \kappa_Z \equiv \kappa_V$.

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

$$a_g a_V = (\sigma/\sigma_{\rm SM})(gg \to h \to VV^*) = 0.92 \pm 0.15$$

Using measurements for $a_g a_V$, $a_g a_\gamma$, $a_{\rm VBF} a_\gamma$:

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

for $f_g = 0$.

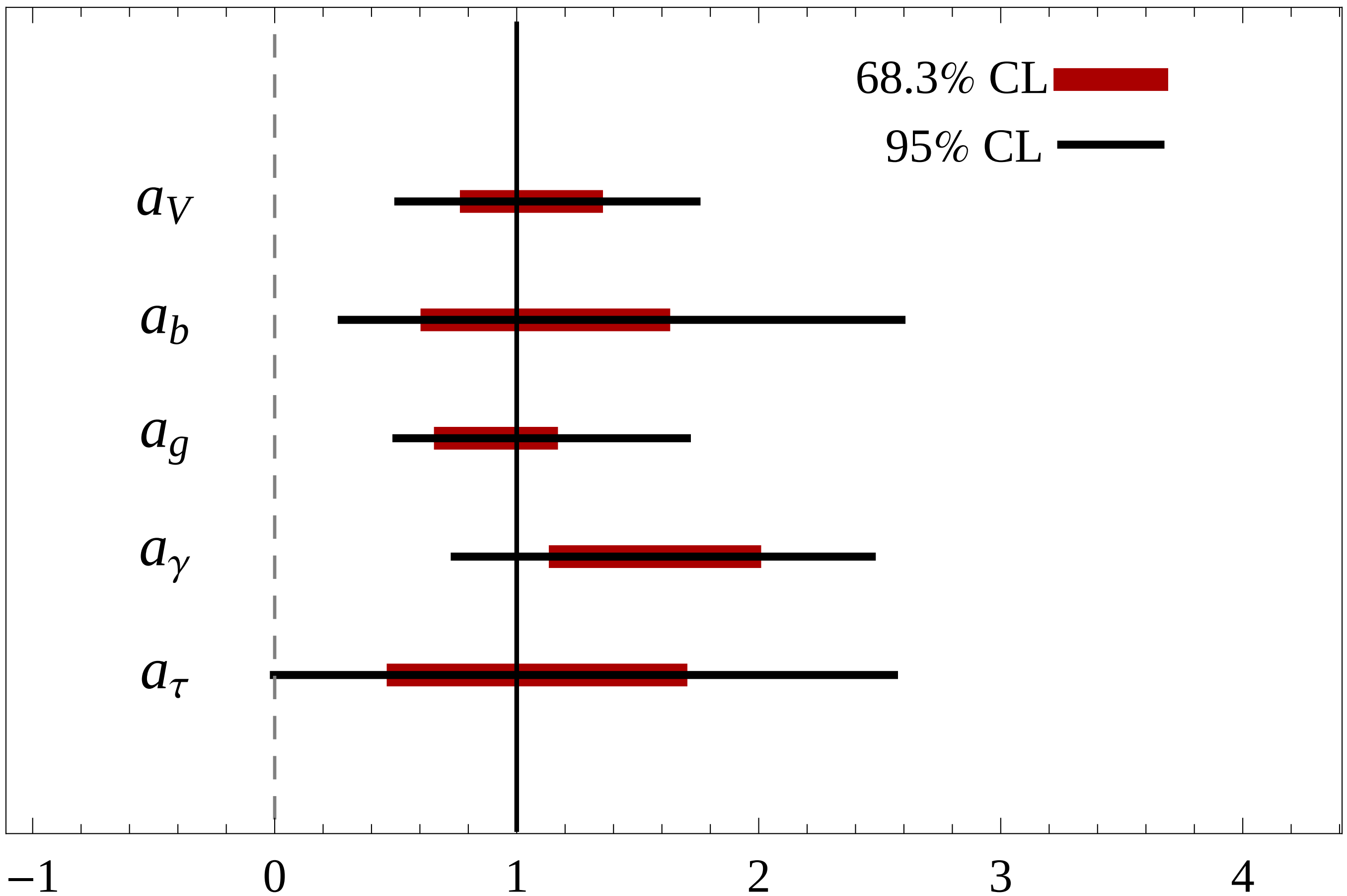
Using (bifurcated) Gaussian distributions,

$$a_V = 1.00^{+0.34}_{-0.22}$$

Similarly, extract a_g, a_γ. Measurements for $a_V a_b$, $a_g a_\tau$ give a_b and a_τ.

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

Intervals for 'apparent squared-couplings':



for $f_g = 0$, and including the VBF data only for $h^0 \to \gamma\gamma$.

Lower limit on Γ_h

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

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

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

Given that $\Gamma_X \geq 0$,

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

Lower limit on the width:

$$\Gamma_h \geq \Gamma_h^{\rm min} = 0.90^{+0.78}_{-0.25} \, \Gamma_h^{\rm SM}$$

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

$$0 < \kappa_W = \kappa_Z \leq 1$$

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

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

$$|\kappa_W| < \kappa_W^{\max} \quad , \quad |\kappa_Z| < \kappa_Z^{\max}$$

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

Upper limit on Γ_h

The upper limits on κ_W and κ_Z imply

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

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

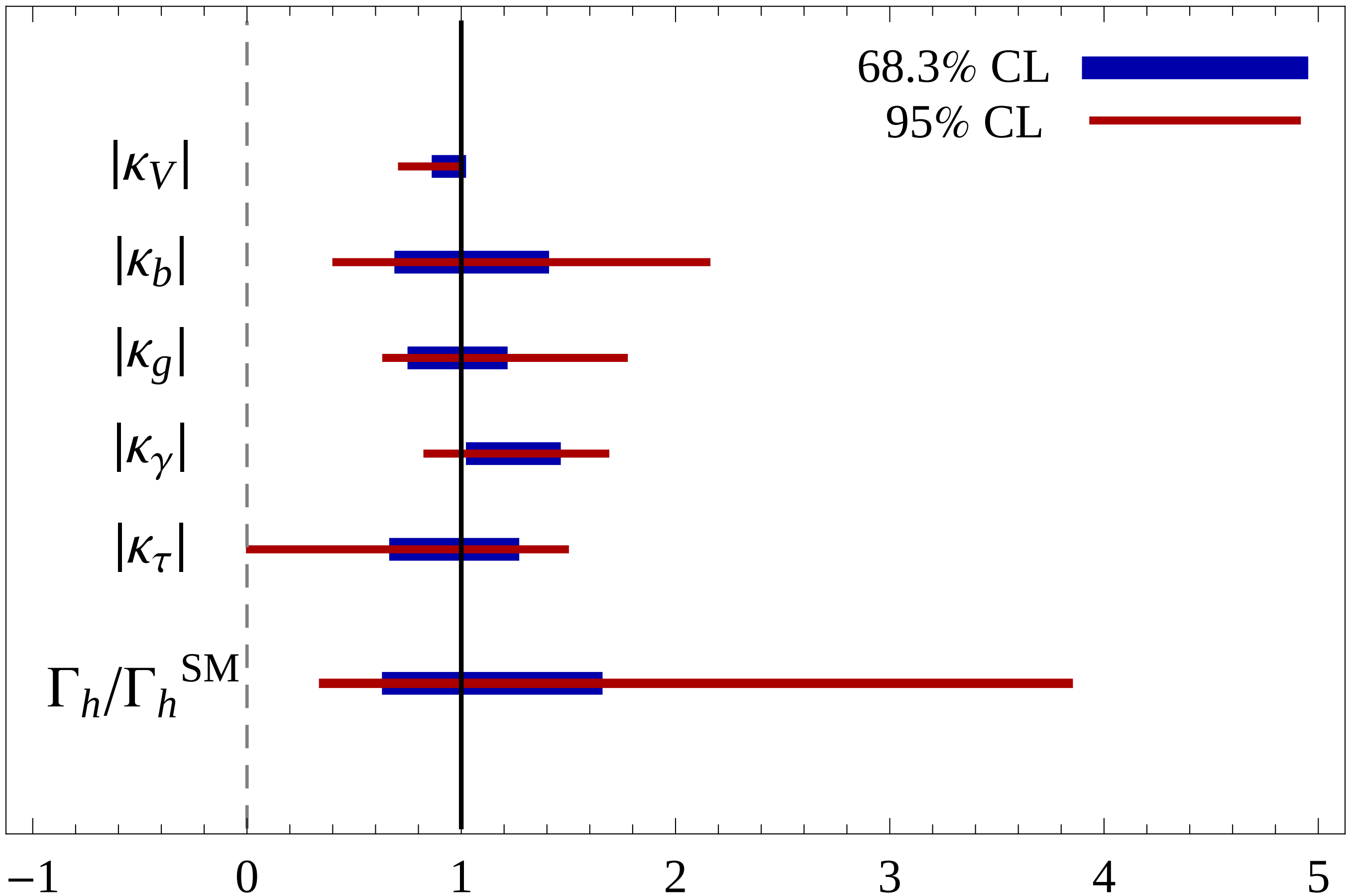
$$\Gamma_h \le \Gamma_h^{\max} = \frac{\Gamma_h^{\mathrm{SM}}}{a_V^2}$$

a_V extracted from the current data gives:

$$\Gamma_h \le \Gamma_h^{\max} = 0.71^{+0.93}_{-0.15}\, \Gamma_h^{\mathrm{SM}}$$

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

Coupling 'spans':



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

Branching fraction of exotic decays:

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

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

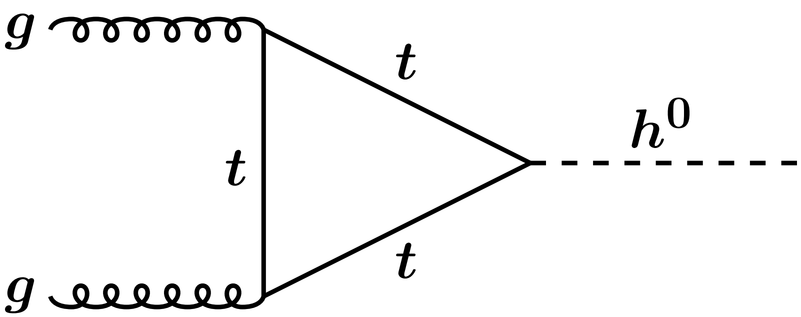
$$\Rightarrow \quad \mathcal{B}_X \leq \mathcal{B}_X^{\max} = 1 - \left(\frac{\Gamma_h^{\mathrm{SM}}}{\Gamma_h^{\max}}\right)^{1/2} \sum_{\substack{\mathcal{P} = W, Z, \\ b, \tau, g, \gamma}} a_{\mathcal{P}} \, \mathcal{B}^{\mathrm{SM}}(h^0 \to \mathcal{P}\mathcal{P})$$

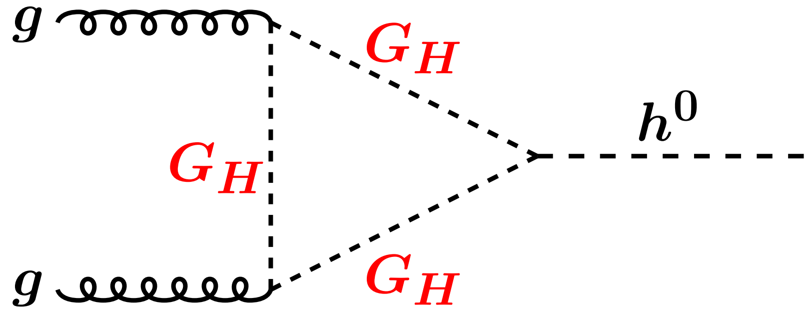
$\mathcal{B}_X^{\max} < 22\%$ **at the 68% CL**

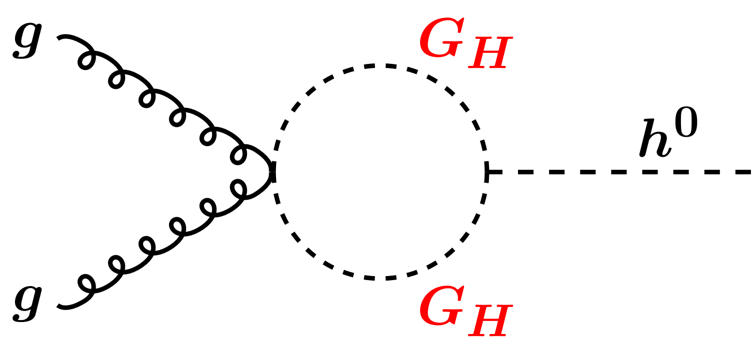
$\mathcal{B}_X^{\max} < 46\%$ **at the 95% CL.**

Non-standard Higgs production

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







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

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

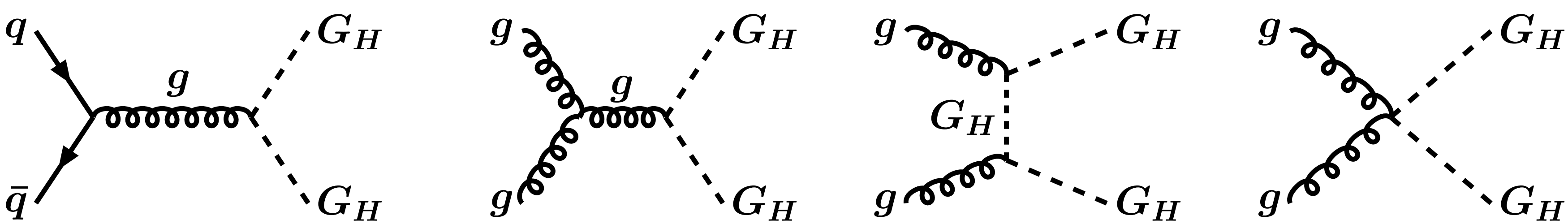
Scalar octet

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.

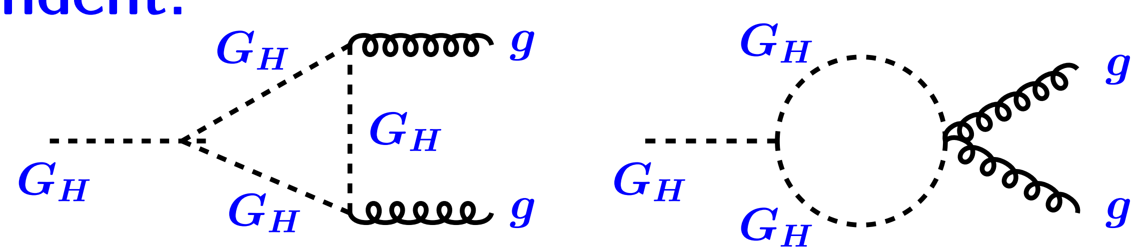


Dobrescu, Kong, Mahbubani, hep-ph/0709.2378

G_H decays are model dependent.

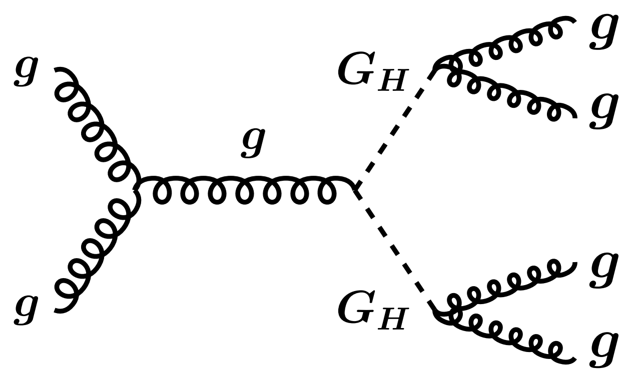
A simple possibility: $G_H \rightarrow gg$

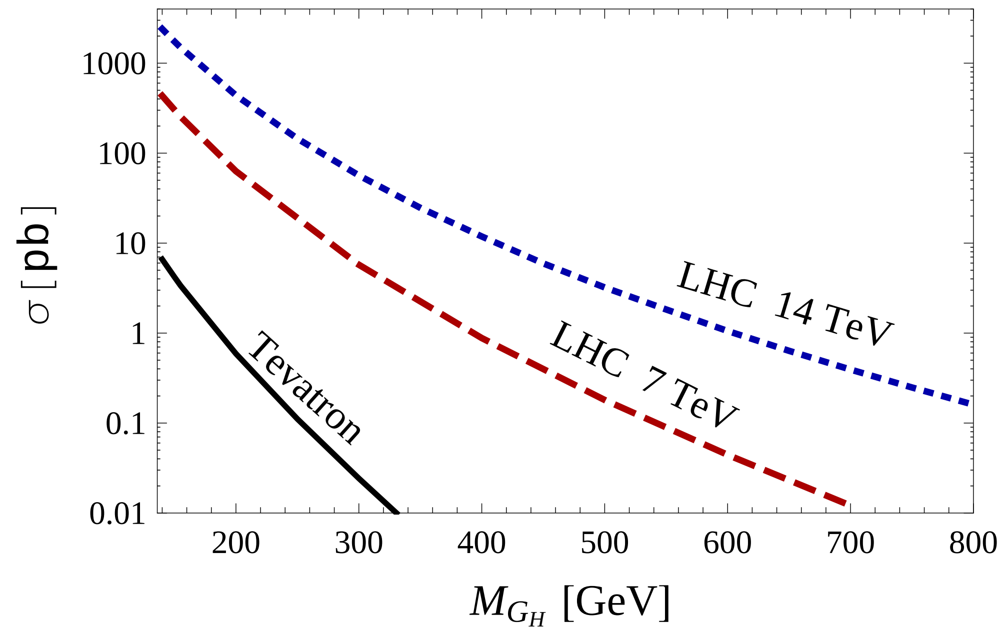
Dobrescu, Bai, 1012.5814

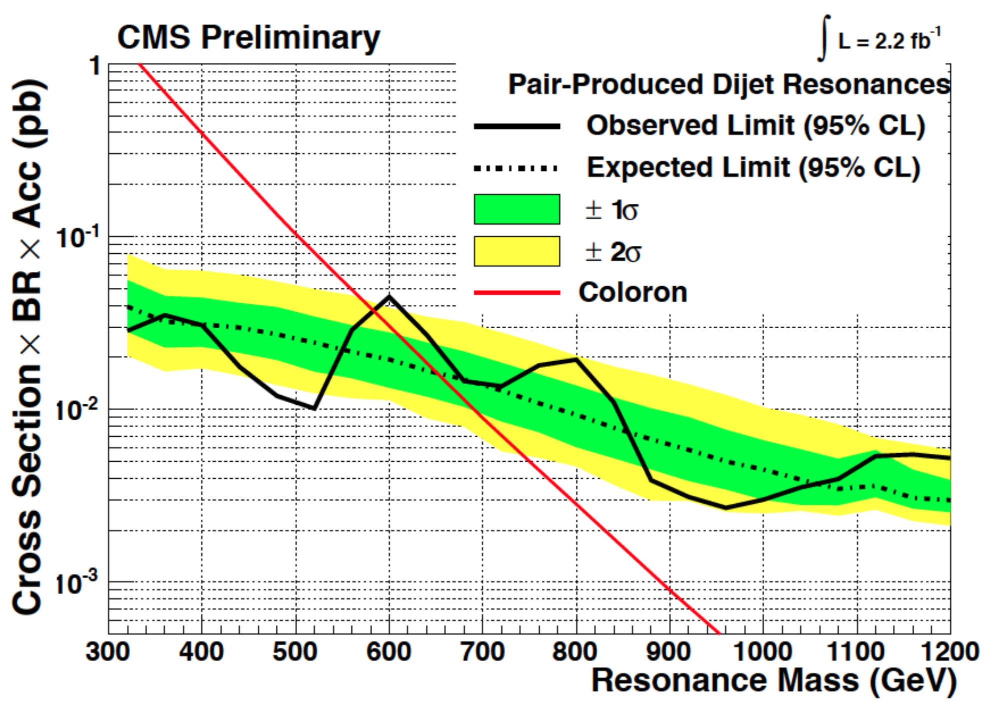


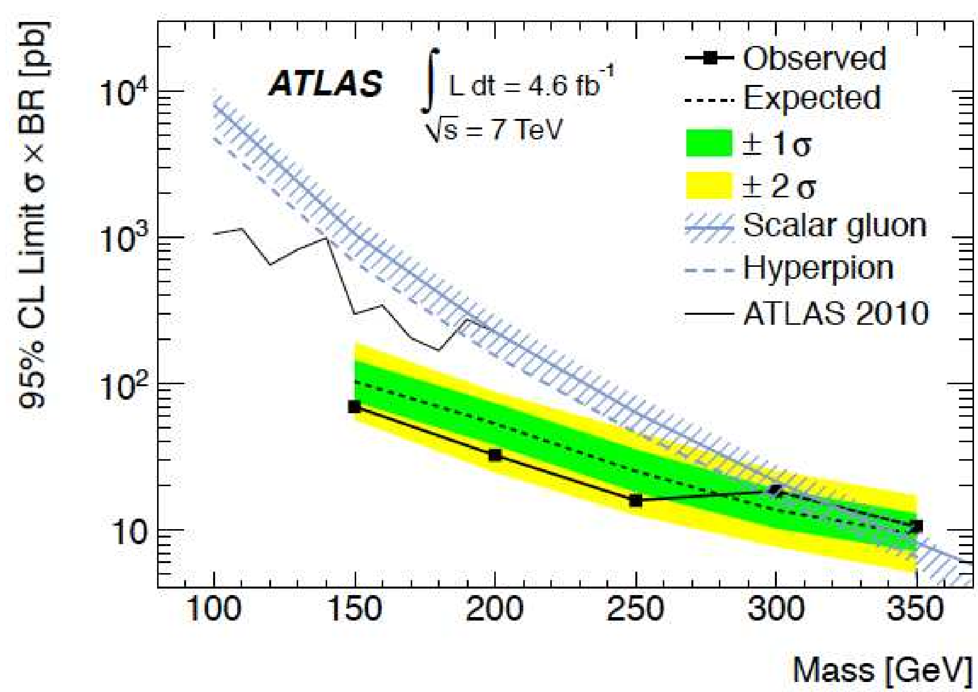
A more complicated decay: $G_H \rightarrow \bar{\psi}^* \psi^* \rightarrow g\bar{q}\,gq$

Signal: a pair of narrow gg resonances of same mass





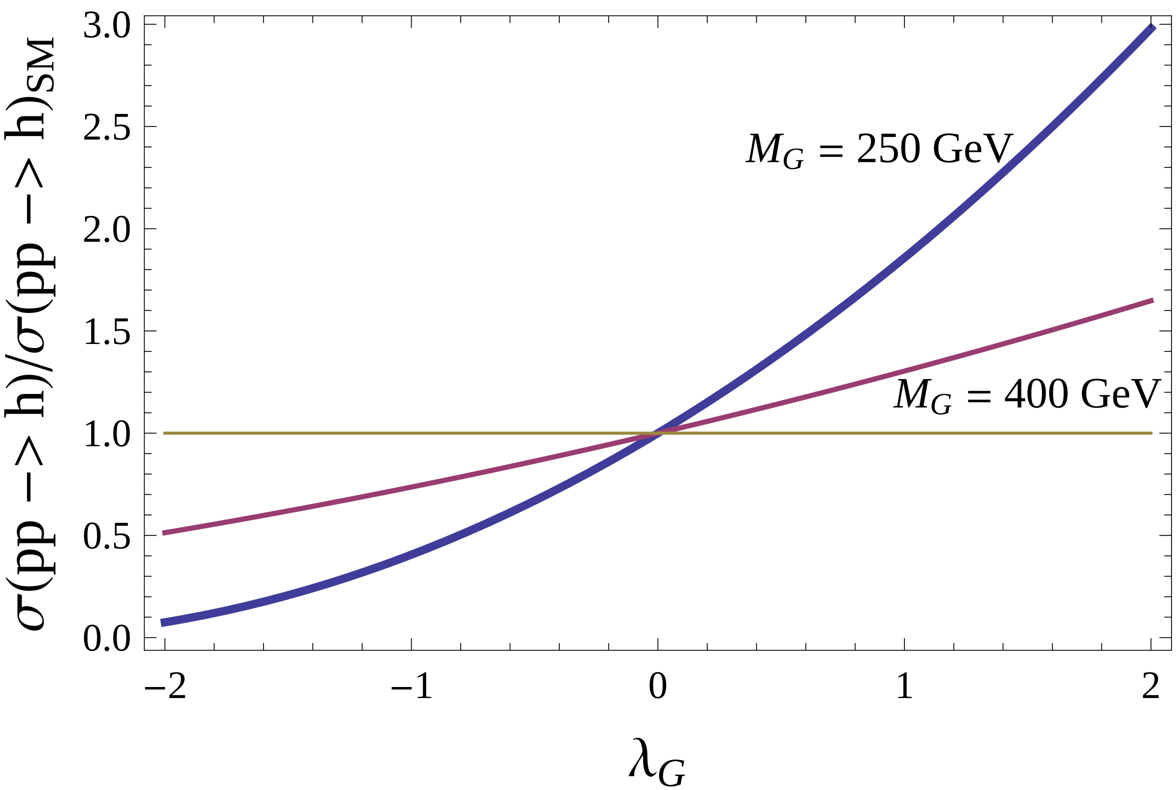




ATLAS search for $(jj)(jj)$

For $M_h^2 \ll M_{G_H}^2$**:** $\kappa_g \approx 1 + 3\lambda_G \frac{v_h^2}{8M_{G_H}^2}$

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)

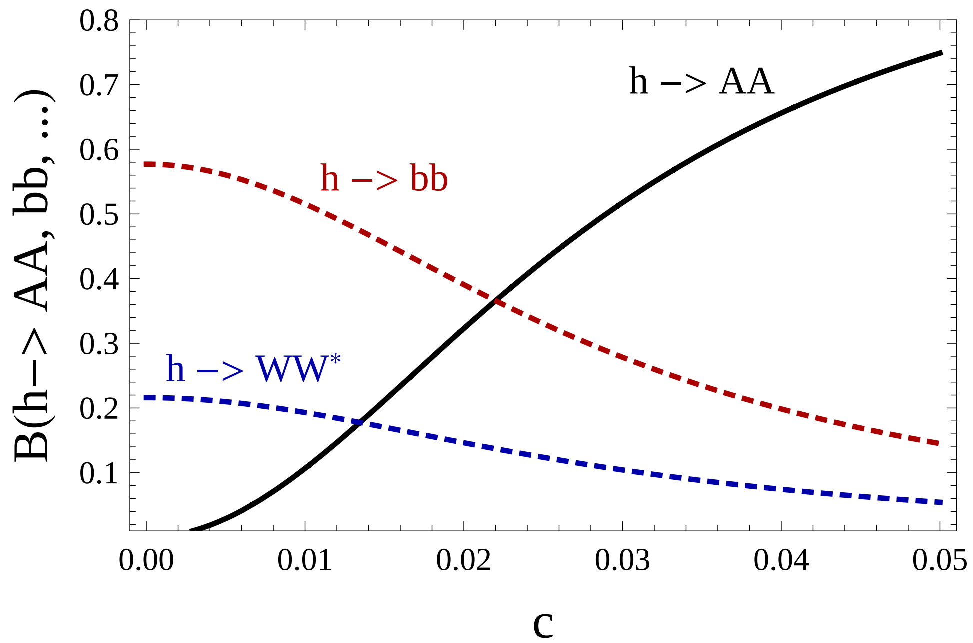
Nonstandard Higgs decays

Standard model + a gauge-singlet complex scalar S:

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

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

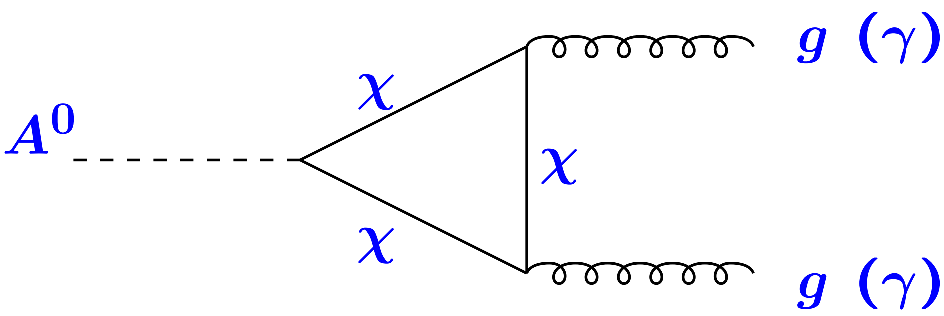
For $2M_A \ll M_h = 125$ GeV:



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:

$$\mathcal{B}(A^0 \rightarrow gg) \gtrsim 99\%.$$

Even $\mathcal{B}(h \rightarrow A^0 A^0 \rightarrow 4\, g)$ 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.

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

Vectorlike quarks

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

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

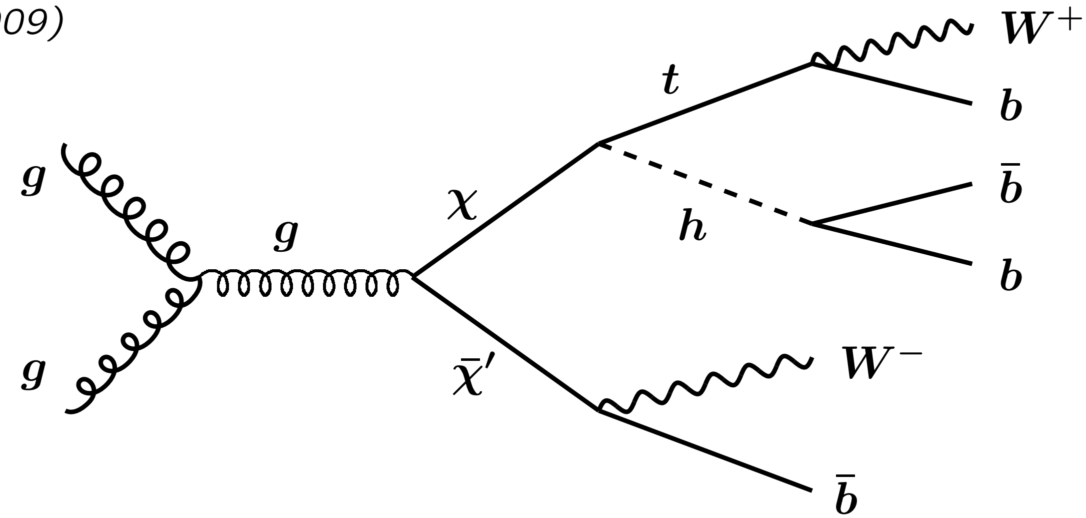
– a new (hypothetical) form of matter.

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

$\Rightarrow$ naturally heavier than the t quark.

A vectorlike quark χ which mixes with the top quark:

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

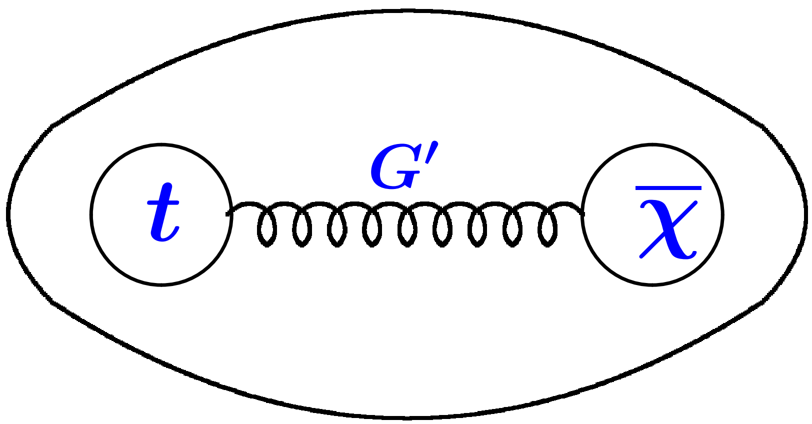


Higgs boson may lead to the discovery of the vectorlike quark.

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 sensitive to various phenomena beyond the SM.

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.

$\Gamma_h < \Gamma_{\rm max}$ $\Rightarrow$ **an upper limit on the branching fraction of exotic Higgs decays** *(46% at the 95% CL, if the electroweak symmetry is broken only by doublets).*