Consequences of Suppressed Higgs Decays to Photons at the LHC

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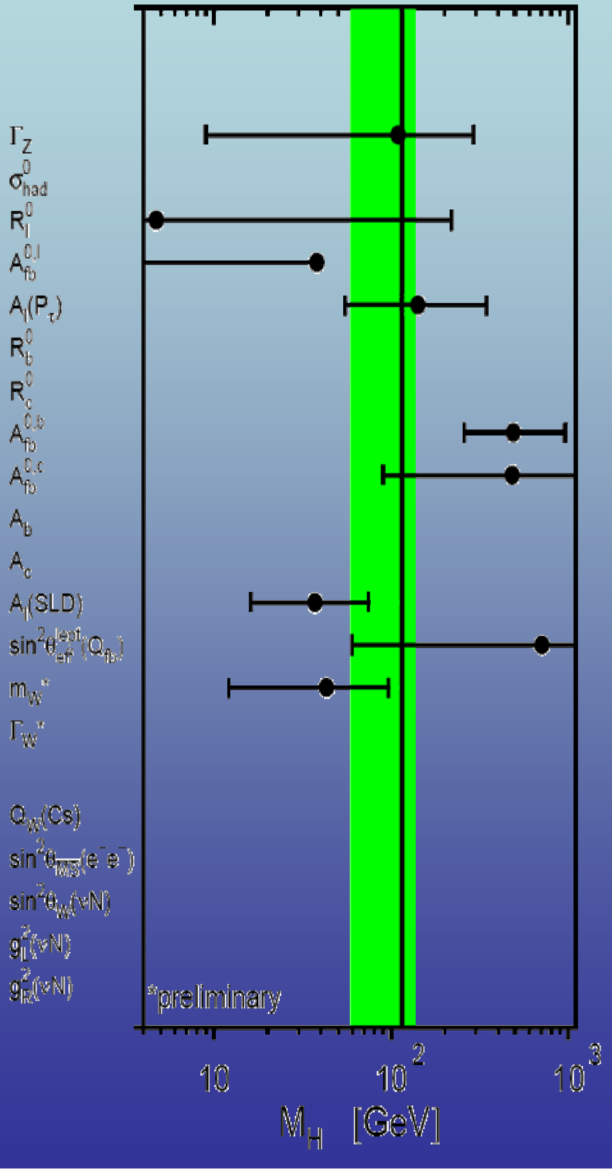
- Based on [hep-ph/0612219] (Phalen, Thomas, and Wells).

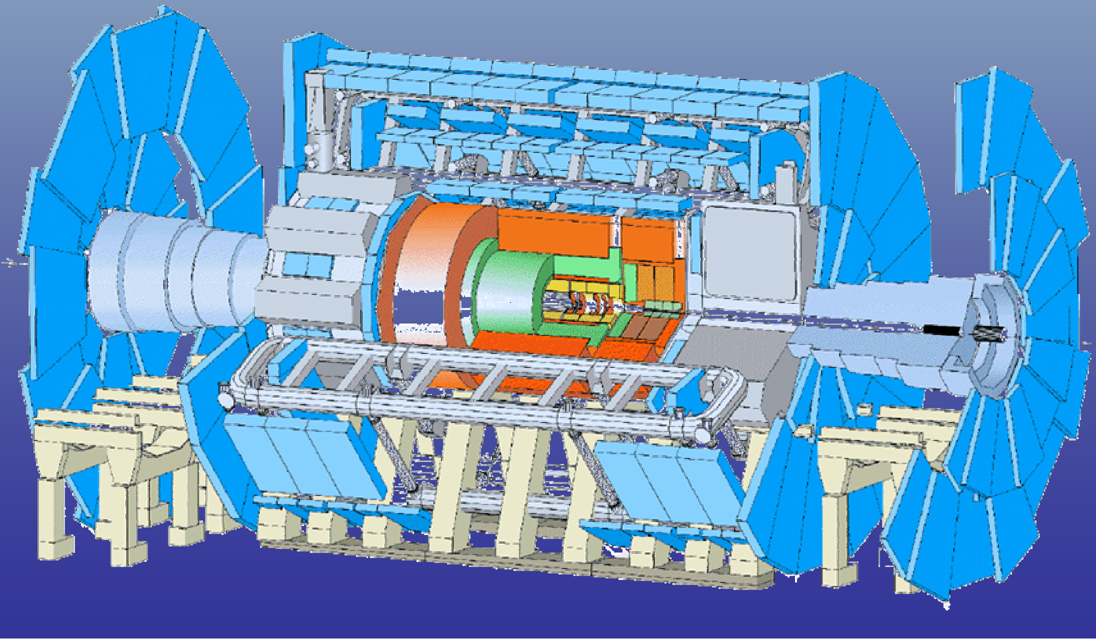
What do we know about EWSB?



- In the Standard Model, a single Higgs doublet is responsible for the spontaneous breaking of $SU(2) \times U(1)$ down to $U(1)_{EM}$.
- Experimental data are still consistent with the the Standard Model description of electroweak symmetry breaking (EWSB), but the window for the Higgs boson mass is shrinking.
- Precision electroweak measurements strongly prefer a Higgs mass $m_h \lesssim 200$ GeV, while LEP direct detection bounds indicate a Higgs mass $m_h \gtrsim 100$ GeV.
- Considerations related to naturalness and the hierarchy problem suggest that the Standard Model should be regarded as an effective description of some high-energy theory.
- The moral: we don't yet know EWSB works or how many effects contribute to it.

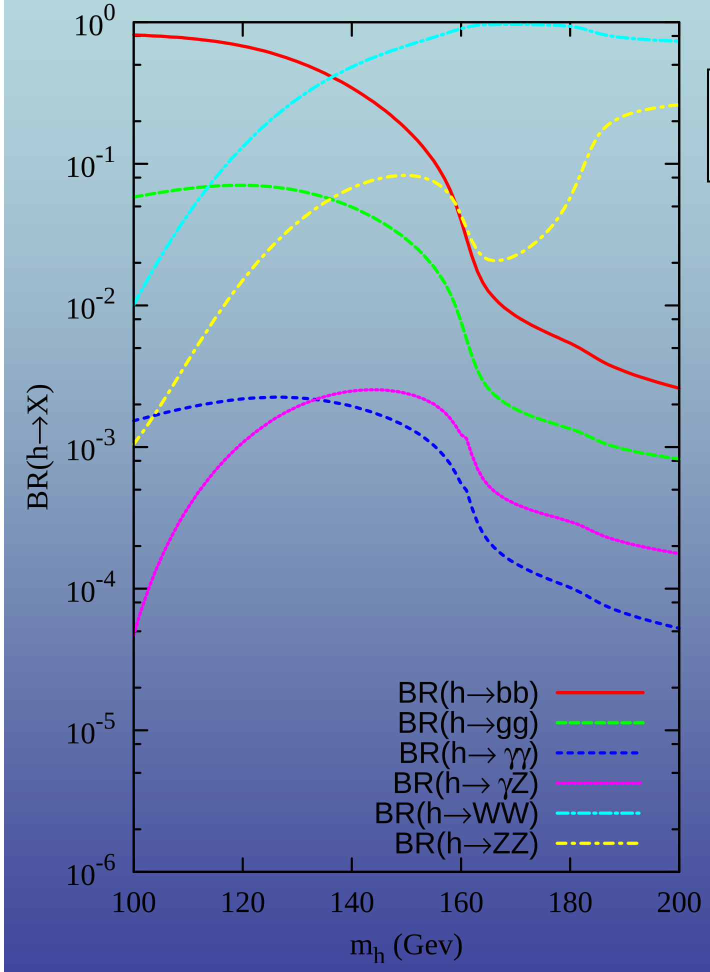
Higgs Physics in the LHC Era

- The Large Hadron Collider (LHC), a pp collider with $\sqrt{s} = 14$ TeV will soon begin taking data.
- We have good reason to expect that a great deal more information about the mechanism (or mechanisms) responsible for EWSB will manifest themselves at these energies.
- However, we must be careful in interpreting LHC data not to assume that the low-energy effective description is identical to the Standard Model, especially in the Higgs sector, where we have the least information.



- Models which "look like" the Standard Model in that their low-energy effective description contains one light Higgs boson may result in patterns of collider observables that differ radically from those expected in the Standard Model.

Collider Physics of an SM Higgs



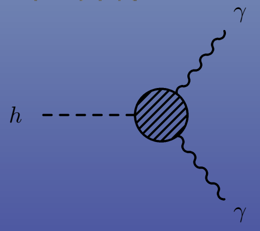
- The Standard Model Higgs Lagrangian contains terms:

$$\mathcal{L} = \frac{1}{2}(D^{\mu}\phi)^{\dagger}D_{\mu}\phi - \mu\phi^{\dagger}\phi - \frac{\lambda}{4}(\phi^{\dagger}\phi)^{2} + (y_{d_i}\phi\bar{q}_i d + y_{u_i}\phi\bar{q}_i u) + h.c$$

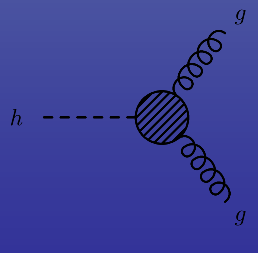
- The light, CP-even Higgs boson that remains in the spectrum after EWSB couples to fermions and gauge bosons with strengths:

$$g^{sm}_{hff} = \frac{m_f}{v} \qquad g^{sm}_{hWW} = \frac{g^2 v}{2} = \sqrt{2}gM_W$$

- Effective couplings hgg and $h\gamma\gamma$ are generated by loop effects.



$$\longrightarrow \quad \left(F_1(\tau_W) + \frac{4}{3}F_{1/2}(\tau_t)\right)\frac{h}{v}\frac{\alpha}{8\pi}F_{\mu\nu}F^{\mu\nu}$$



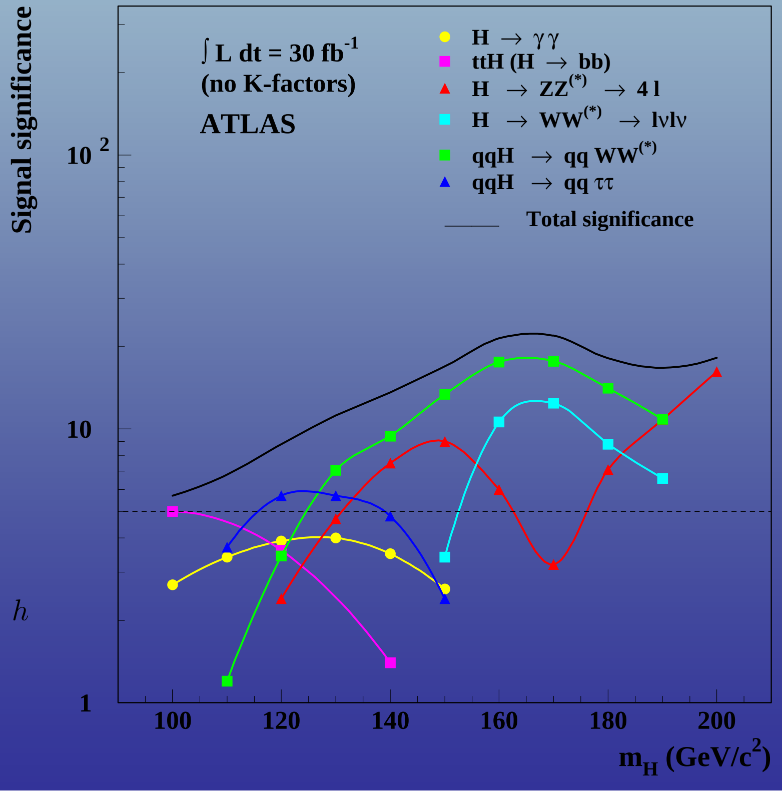
$$\longrightarrow \quad F_{1/2}(\tau_t)\frac{h}{v}\frac{\alpha_s}{8\pi}G^{a}_{\mu\nu}G^{a\mu\nu}$$

Detecting a SM Higgs at the LHC

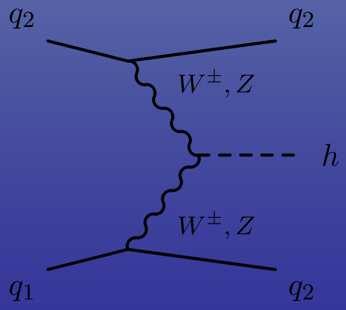
- In the mass range 115 GeV $\lesssim m_h \lesssim$ 150 GeV, there are three channels that are particularly useful discovering a Higgs boson.
- $gg \to h \to \gamma\gamma$ is particularly useful due to the low invariant mass resolution.
- $h \to WW^*$ and $h \to ZZ^*$ become important for $m_h \gtrsim$ 135 GeV.

(plot from Asai et al., 2004)

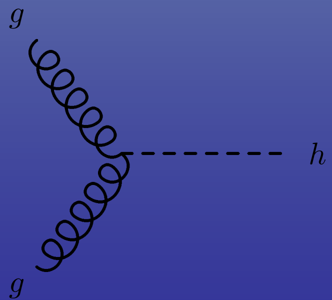
- Weak boson fusion processes are also significant.
- $t\bar{t}h$ processes, although important at lower energies, are not terribly important for a Standard Model Higgs in this mass range.



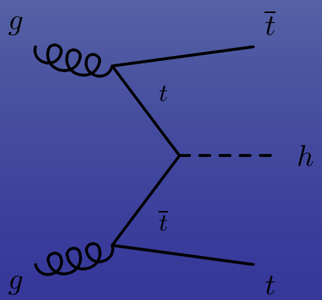
WBF



Gluon Fusion



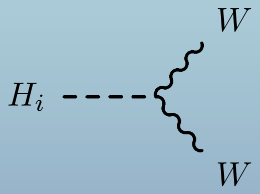
tth



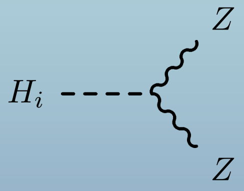
More Complicated Higgs Sectors

- In multi-Higgs modles, the couplings of a Higgs boson to WW and ZZ are proportional to that Higgs's contribution to EWSB.

$$v^2 = \sum_i^n v_i^2$$



$$= \frac{g^2 v_i}{2}$$



$$= (g^2 + g'^2)\frac{v_i}{2}$$

- The Higgs couples to the Standard Model quarks and leptons through Yukawa-type interactions.

Standard Model

$$y = \frac{m_f}{v}$$

Mixing between mass, gauge eigenstates: C_S

Mixing between VEVs: C_V

More Complicated Model

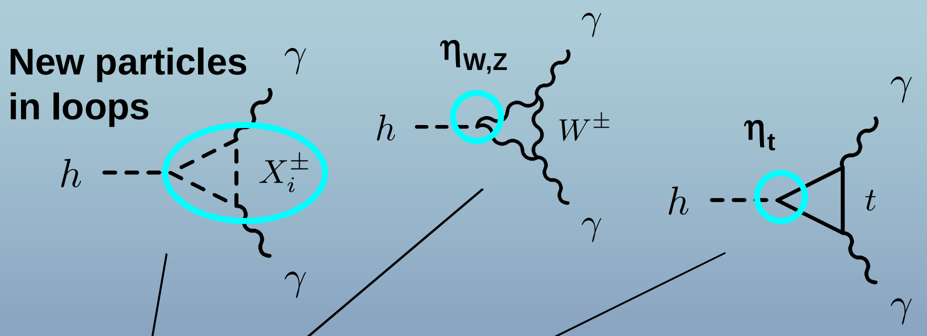
$$y = \left(\frac{C_S}{C_V}\right)\frac{m_f}{v}$$

- Both of these effects can involve complicated functions of mixing angles, but we can parametrize them using coefficients $\eta_{W,Z}$ and η_f.

$$g_{hWW}^{sm} \rightarrow \eta_{W,Z}\, g_{hWW}^{sm} \qquad g_{hZZ}^{sm} \rightarrow \eta_{W,Z}\, g_{hZZ}^{sm} \qquad g_{hff}^{sm} \rightarrow \eta_f\, g_{hff}^{sm}$$

The hgg and hγγ Effective Vertices

- In addition to its tree-level couplings, the Higgs couples to gluons and to photons at the one-loop level.
- These couplings can be modified both by the η_f and η_W coefficients and by the presence of new physics (exotic particles, new effective couplings, etc.).



Higgs-Photon Coupling:

$$\left(F_1(\tau_W)+\frac{4}{3}F_{1/2}(\tau_t)\right)\frac{h}{v}\frac{\alpha}{8\pi}F_{\mu\nu}F^{\mu\nu} \longrightarrow \left(\delta_\gamma+\eta_W F_1(\tau_W)+\eta_t\frac{4}{3}F_{1/2}(\tau_t)\right)\frac{h}{v}\frac{\alpha}{8\pi}F_{\mu\nu}F^{\mu\nu}$$

Higgs-Gluon Coupling:

$$F_{1/2}(\tau_t)\frac{h}{v}\frac{\alpha_s}{8\pi}G^a_{\mu\nu}G^{a\mu\nu} \longrightarrow \left(\delta_g+\eta_t F_{1/2}(\tau_t)\right)\frac{h}{v}\frac{\alpha_s}{8\pi}G^a_{\mu\nu}G^{a\mu\nu}$$

$$\begin{aligned} F_{1/2}(\tau) &= -2\tau[1+(1-\tau)f(\tau)] \\ F_1(\tau) &= 2+3\tau+3\tau(2-\tau)f(\tau) \end{aligned}$$

$$f(\tau)=\begin{cases} \arcsin^2(1/\sqrt{\tau}) & \tau\geq 1 \\ -\frac{1}{4}\left[\ln(\eta_+/\eta_-)-i\pi\right]^2 & \tau<1 \end{cases}$$

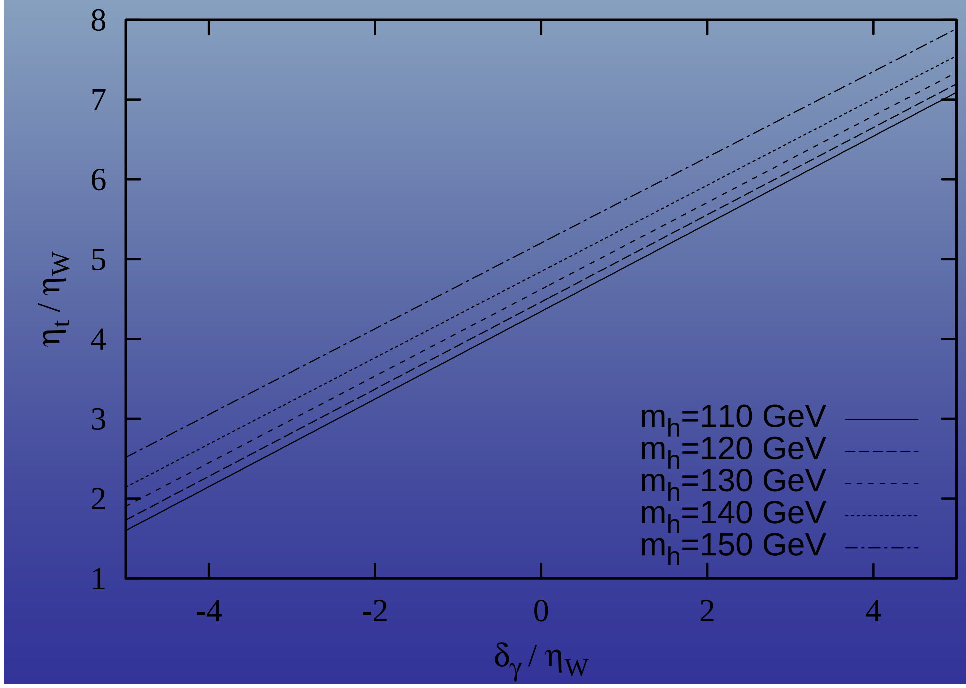
$$\tau_i = 4m_i^2/m_h^2$$

Shutting Off h→γγ

- Except in a few unusual cases (radion in warped extra dimensions, nonrenormalizable operators with a low-scale cutoff), δ_γ and δ_g will generally be quite small.
- $h\gamma\gamma$ is unique in that it contains terms proportional to both $\eta_{W,Z}$ and η_f. This leads to the possibility of cancelations between terms even for small δ_γ.

$$\left(\frac{\eta_t}{\eta_W}\right) = -\frac{3}{4}\left(\frac{1}{F_{1/2}(\tau_t)}\left(\frac{\delta_\gamma}{\eta_W}\right) + \frac{F_1(\tau_W)}{F_{1/2}(\tau_t)}\right) \longrightarrow$$

No effective hγγ vertex!



- For a Higgs boson in the mass range 115 GeV $\lesssim m_h \lesssim$ 150 GeV, the Higgs coupling will be significantly reduced when $4 \lesssim \eta_f/\eta_{W,Z} \lesssim 5$ (for small δ_γ).
- BR($h \to \gamma\gamma$) can also be suppressed when the total width of h is large, as it is in certain regions of SUSY parameter space where $\Gamma(h \to b\bar{b})$ is amplified.

Type I Higgs Scenarios

- We consider a Higgs sector consisting of two Higgs doublets Φ_{EW} and Φ_f. Φ_f contributes both to EWSB and to fermion mass generation; Φ_{EW} contributes to EWSB only (decoupled from fermions).
- $v^2 = v_{sm}^2 = v_f^2 + v_{EW}^2$.
- In this case, $\eta_{W,Z}$ and η_f are described entirely in terms of two mixing angles α and β, defined (as in Supersymmetry) by:

$$\tan\beta = \frac{v_f}{v_{EW}} \qquad \begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \sqrt{2}\mathrm{Re}(\Phi_{EW}^0) \\ \sqrt{2}\mathrm{Re}(\Phi_f^0) \end{pmatrix}$$

Consequences of mixing:

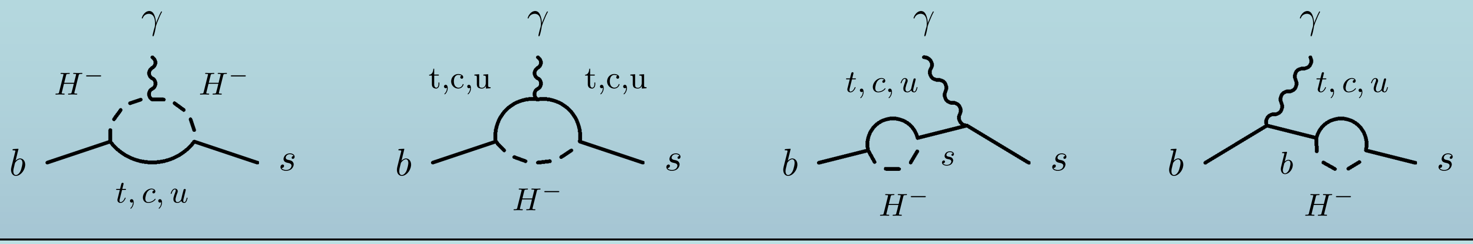
- The η parameters then are:

$$\eta_f = \frac{\cos\alpha}{\sin\beta} \qquad \eta_{W,Z} = \sin(\beta-\alpha)$$

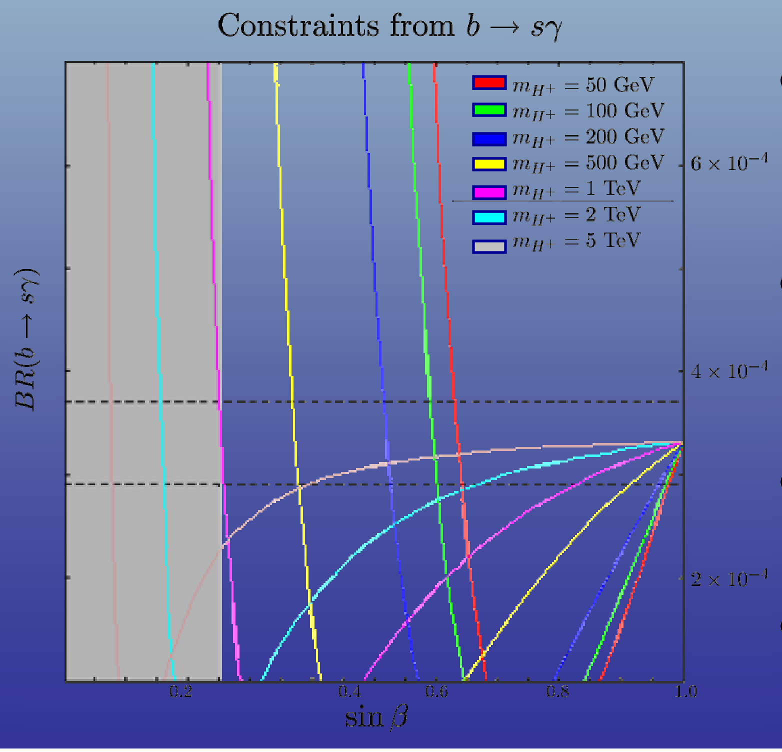
- The requirement that the top quark Yukawa coupling be perturbative places a lower bound on $\sin\beta$:

$$y_{\Phi tt} = \frac{m_t}{v\sin\beta} \lesssim 4 \longrightarrow \sin\beta \gtrsim 0.250$$

Other limits on sinβ



$$\Gamma(b \to s\gamma) = \frac{\alpha G_F^2 m_b^5}{128\pi^4} \left| \sum_{i=u,c,t} V_{is}^* V_{ib} \left[G_W(x_i) - \cot^2\beta G_H^{(1)}(y_i) + \cot^2\beta G_H^{(2)}(y_i) \right] \right|^2$$



- Bounds on $\sin\beta$ can be derived from the results of $K_L - K_S$ and $B^0 - \overline{B}^0$ mixing experiments, as well as from limits on $b \to s\gamma$.
- The most stringent limit comes from $b \to s\gamma$. The combined bound from CLEO and Belle is $BR(b \to s\gamma) = ((3.3 \pm 0.4) \times 10^{-4}$.
- The charged Higgs contribution can interfere with the Standard Model amplitude.
- When $m_{H^\pm} \gtrsim$ (afewTeV), all $\sin\beta$ allowed by top perturbativity are permitted.

The Effect on Observables

- The cross-sections for collider observables are altered in three ways by modifying the Higgs couplings.
- $\sigma(XX \to h) \propto \Gamma_h(XX)$ at leading order.

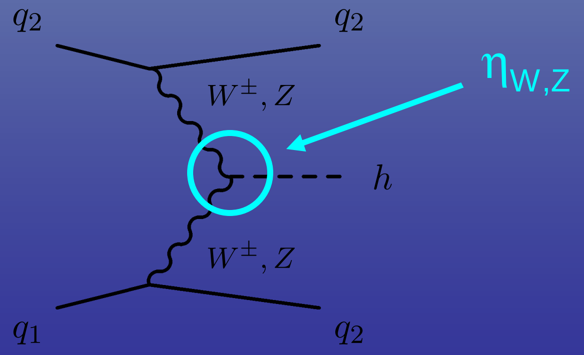
3). Modification of Total Higgs Width

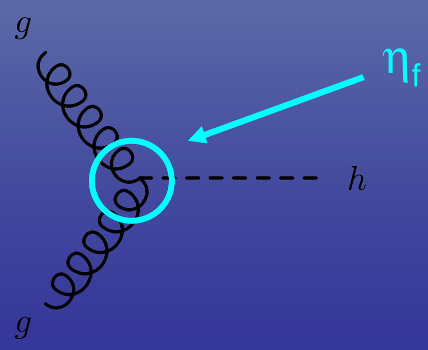
$$\frac{\sigma_h(\gamma\gamma)}{\sigma_h(\gamma\gamma)_{sm}} = \frac{\Gamma_h(gg)}{\Gamma_h(gg)_{sm}}\frac{\Gamma_h(\gamma\gamma)}{\Gamma_h(\gamma\gamma)_{sm}}\left(\frac{\Gamma_h(\text{tot})}{\Gamma_h(\text{tot})_{sm}}\right)^{-1}$$

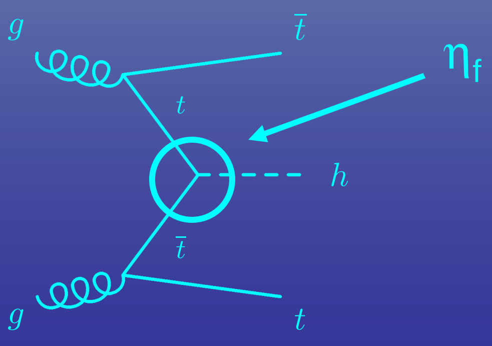
1). Modification of Production Cross Section

2). Modification of Decay Widths

Process	σ_{prod} Multiplier
Gluon fusion	η_f^2 (enhanced)
Weak Boson Fusion	η_W^2 (suppressed)
$t\bar{t}h$	η_f^2 (enhanced)

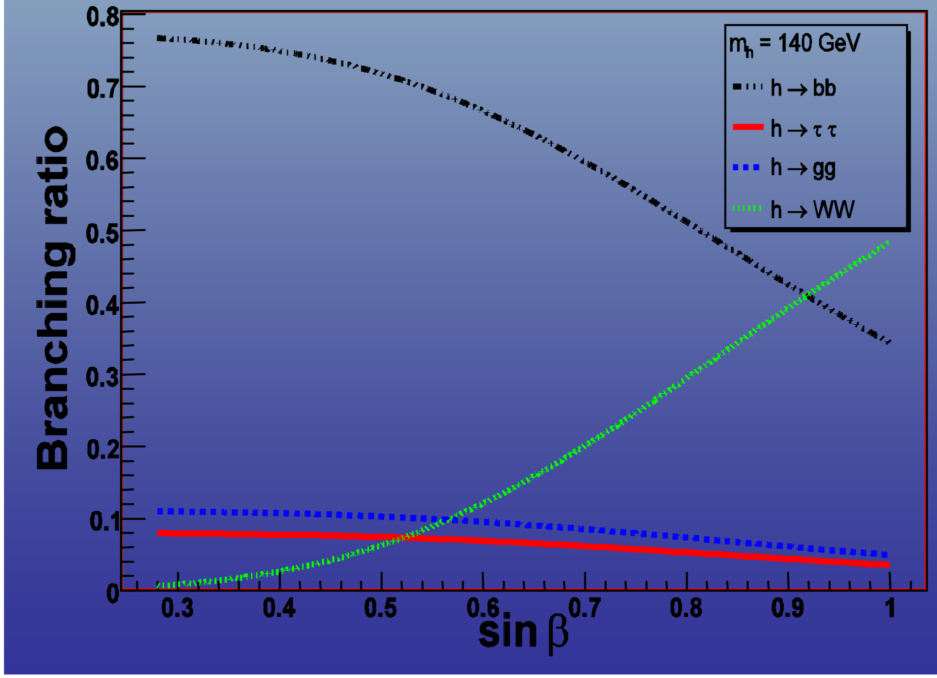






The Effect on Branching Fractions

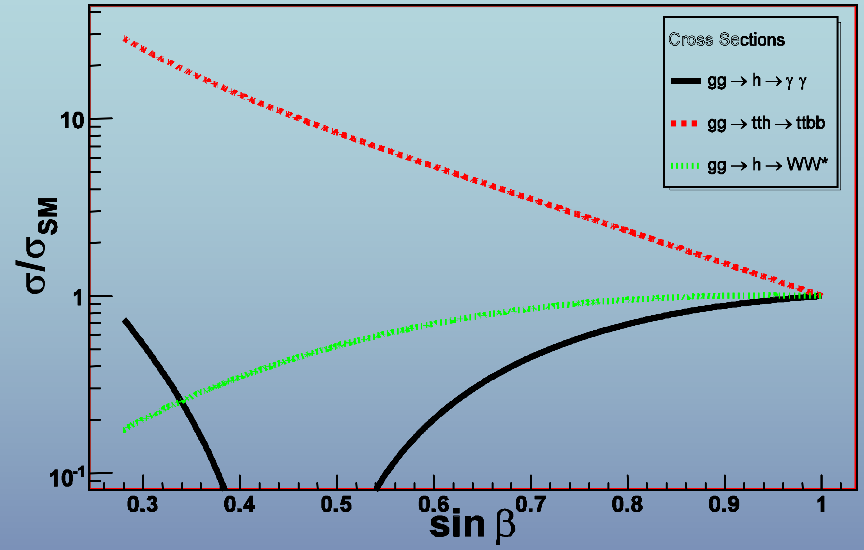
- In the mass range 100 GeV $\lesssim m_h \lesssim$ 135 GeV, Higgs decays are primarily fermionic, $h \to b\bar{b}$, and enhanced by η_f relative to the Standard Model.
- In the mass range 135 GeV $\lesssim m_h \lesssim$ 150 GeV, Higgs decays are primarily bosonic, $h \to WW^*$, and are suppressed relative to the Standard Model.
- When $h \to b\bar{b}$ is the dominant decay mode, the total width of the Higgs is increased by a factor of 3 to 4 over the Standard Model width. As a result, branching fractions are suppressed.

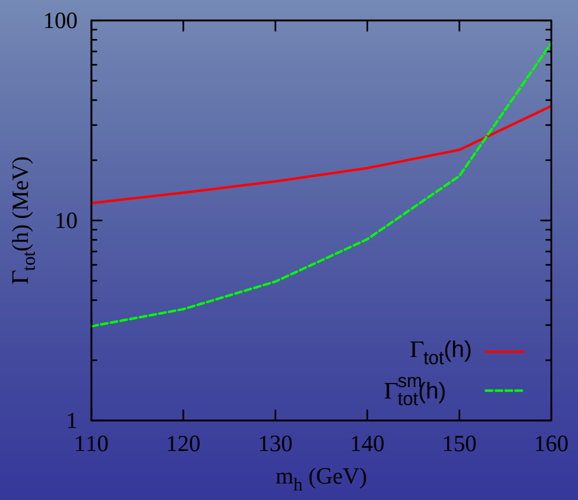


- Our graphs correspond to the choice $m_h =$ 140 GeV and $\alpha = 0$.
- However, for any $a \lesssim 1/2$, $\Gamma(h \to \gamma\gamma)$ still has a zero in the perturbative region and the same qualitative features.

Branching Ratio and Total Width

- When modifications to the production cross section, the partial decay width, and the total Higgs decay width are taken into account, $t\bar{t}h$ processes where the Higgs decays into fermions (most importantly $b\bar{b}$ and) $\tau\overline{\tau}$ are significantly enhanced.
- All other channels relevant for the discovery of a Higgs boson with mass in the range 115 GeV $\lesssim m_h \lesssim$ 150 GeV are suppressed.





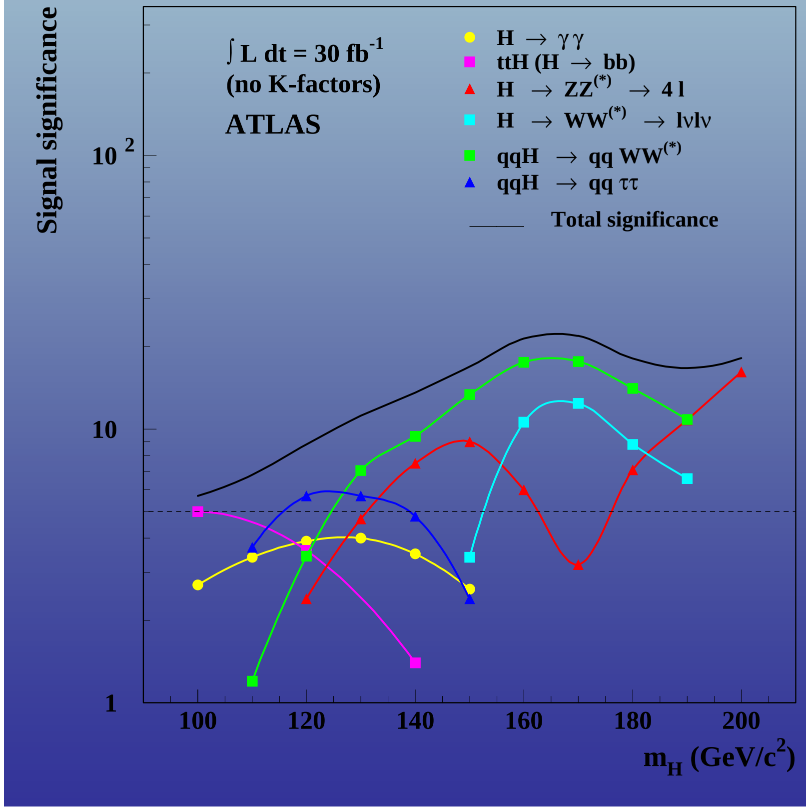
- Altering the Higgs couplings will also modify the total width of the Higgs.
- The invariant mass resolution for diphoton events at ATLAS is around 1.5 GeV for a 130 GeV Higgs boson, so the narrow width approximation is still valid.
- This means that the significance of discovery in each relevant channel can be obtained from scaling up the significance by the same factor that multiplies the associated observable.

Significance of Discovery

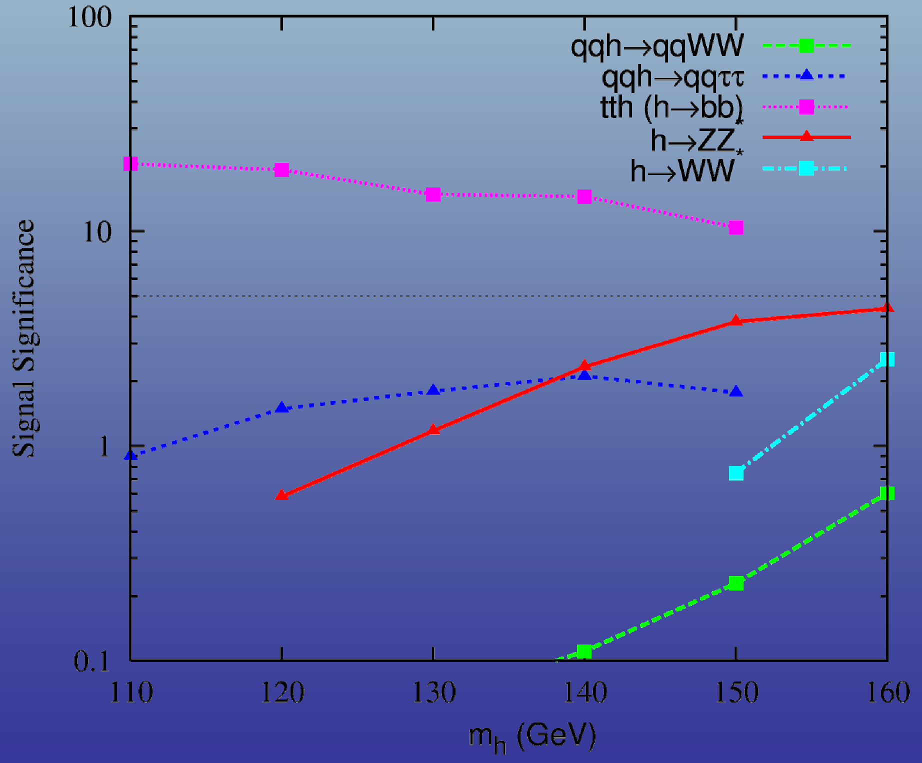
- When the effective $h\gamma\gamma$ vertex is shut off, the only channel in which a 5σ discovery is possible in this mass range, for an integrated luminosity of 30 fb^{-1}, is $t\bar{t}h$, with $h \to b\bar{b}$ or $h \to \tau\bar{\tau}$.

- The upshot: $t\bar{t}h$ processes can be important for higher m_h than usually assumed.

Standard Model



Two-Photon Decay Suppressed



Conclusions

- The Standard Model has been quite successful, but we must make sure not to take too many things for granted when interpreting LHC data.
- Electoweak symmetry breaking may be a complicated process involving contributions from several sources.
- When this is the case, the effective theory may resemble the Standard Model scenario, with one light Higgs boson, but the couplings between this particle and other fields may differ drastically from those of the SM.
- Alterations in these couplings can have dramatic effects on Higgs observables, such as the cross-section for $gg \rightarrow h \rightarrow \gamma\gamma$.
- In situations where the $gg \rightarrow h \rightarrow \gamma\gamma$ cross-section is suppressed, $t\bar{t}h(h \rightarrow b\bar{b})$ becomes by far the most important channel in which to look for a Higgs boson with a mass 115 GeV $\lesssim m_h \lesssim$ GeV.

Acknowledgments

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