Nonstandard Signature Possibilities in Two Higgs Doublet Models

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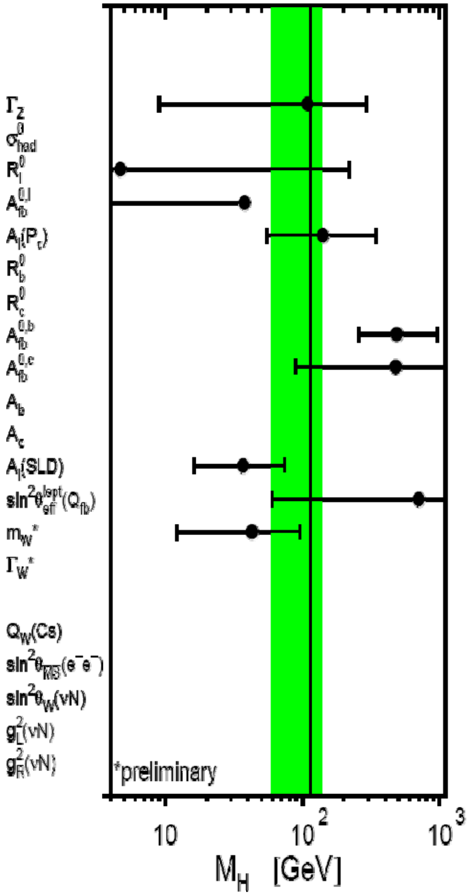
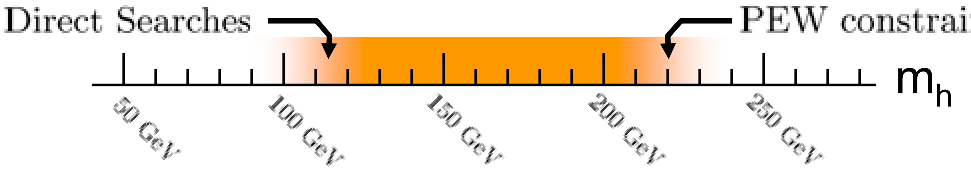
- S. Su and B. Thomas (in preparation)

What do we know about EWSB?



- Not Much. We don't yet know EWSB works or even how many effects contribute to it.
- Experimental data are still consistent with the the SM description of EWSB (i.e. one Higgs doublet), 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 SM should be regarded as an effective description of some high-energy theory.
- One of the primary missions of the LHC is to alleviate our ignorance about EWSB.



One Light Higgs Beyond the SM

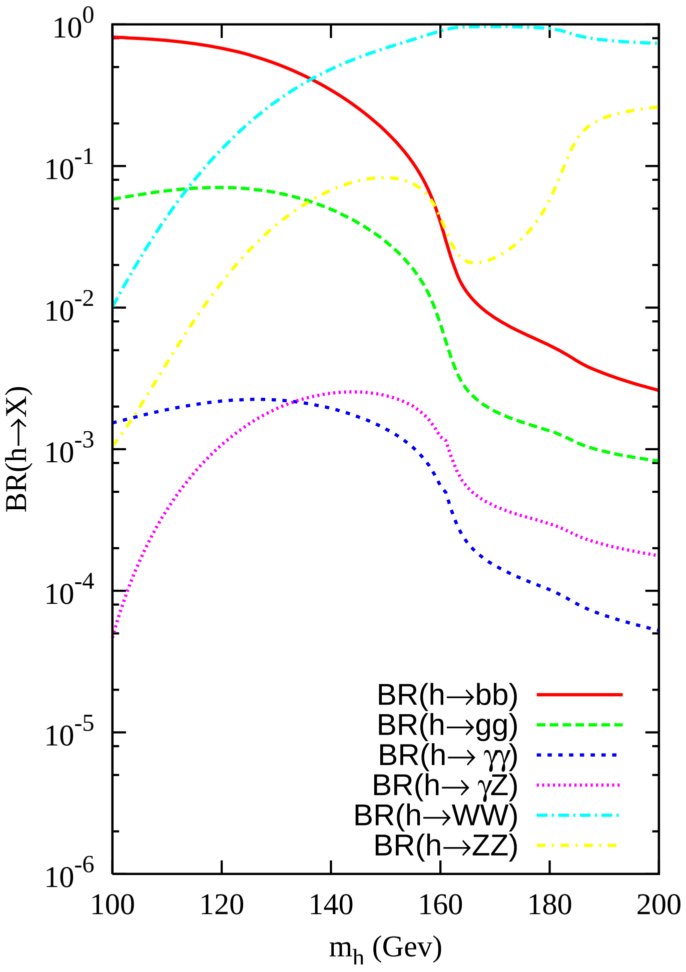
- Here, we consider models that are ”Standard Model-like” in that the weak-scale EFT contains one (and only one) light Higgs boson.
- Examples include SUSY (in the decoupling limit), more general 2HDM (or 3HDM, etc.), and certain Dynamical EWSB models.
- The properties of such a light Higgs in can differ radically from those expected in the SM ⟶ unusual signature patterns at the LHC!

Why look at unusual possibilities?

1). We don’t want to “miss” a light Higgs.

2). Unusual signature patterns provide clues about the underlying theory.

Collider Physics of an SM Higgs



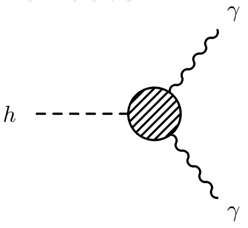
- The Standard Model Higgs Lagrangian contains terms:

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

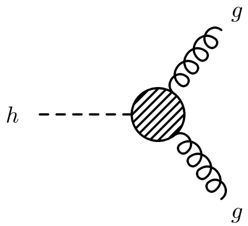
- The light, CP-even Higgs boson that remains in the spectrum after EWSB couples to fermions and gauge bosons with strengths:

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

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



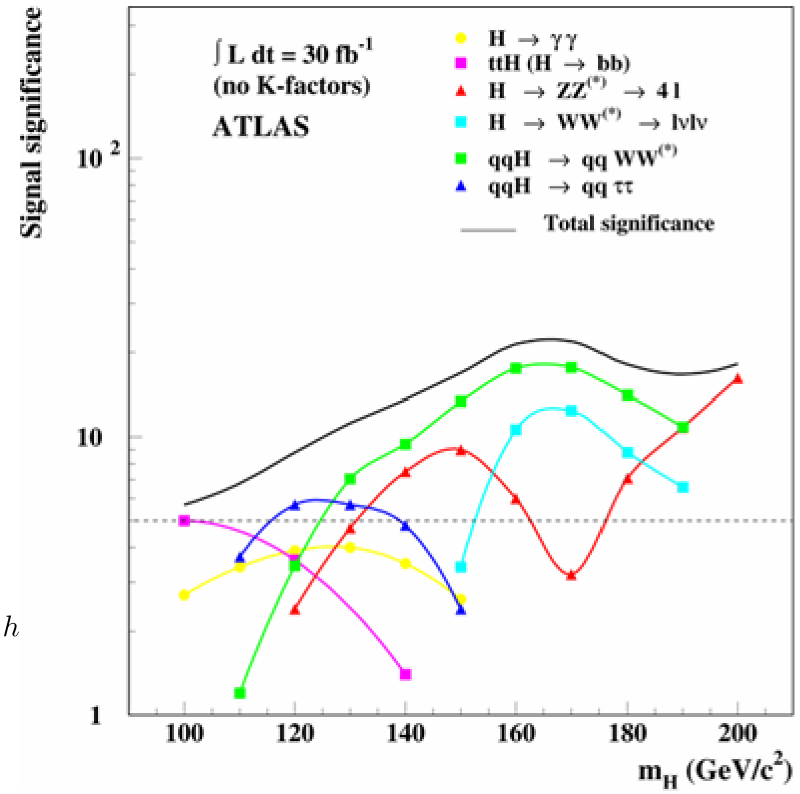
$$\longrightarrow \left(F_1(\tau_W) + \frac{4}{3}F_{1/2}(\tau_t)\right)\frac{h}{v}\frac{\alpha}{8\pi}F_{\mu\nu}F^{\mu\nu}$$



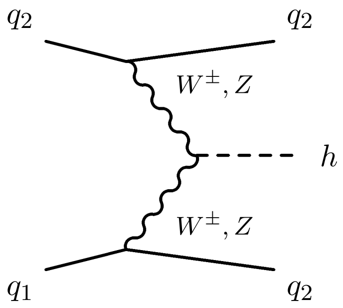
$$\longrightarrow F_{1/2}(\tau_t)\frac{h}{v}\frac{\alpha_s}{8\pi}G^a_{\mu\nu}G^{a\mu\nu}$$

Detecting a SM Higgs at the LHC

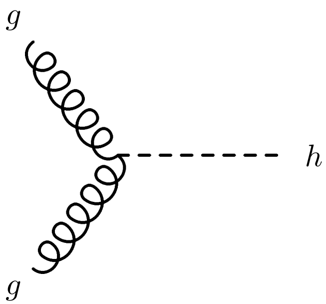
- In the mass range 115 GeV $\lesssim m_h \lesssim$ 150 GeV, there are three channels that are particularly useful discovering a Higgs boson.
- $gg \to h \to \gamma\gamma$ is particularly useful due to the low invariant mass resolution.
- $h \to WW^*$ and $h \to ZZ^*$ become important for $m_h \gtrsim$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



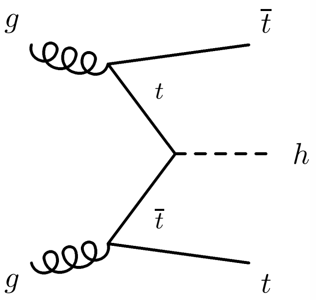
WBF



Gluon Fusion



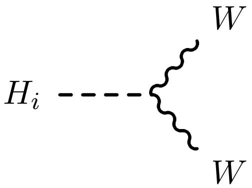
tth



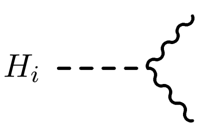
More Complicated Higgs Sectors

- 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

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

Mixing between mass, gauge eigenstates: C_S

$$\longrightarrow$$

Mixing between VEVs: C_V

More Complicated Model

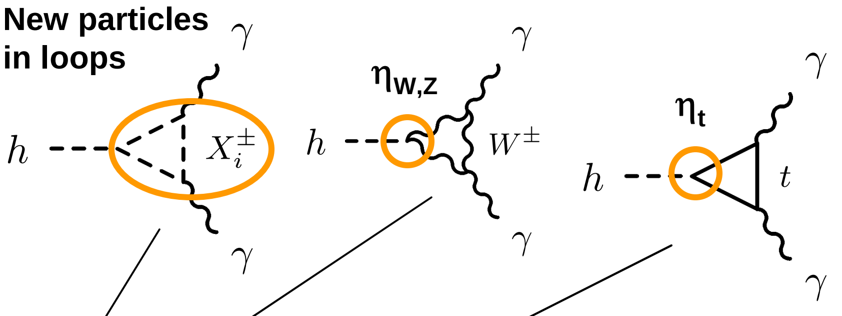
$$\boxed{y = \left(\frac{C_S}{C_V}\right)\frac{m_f}{v}}$$

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

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

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 effective vertices are of pivotal in LHC Higgs phenomenology.
- They can be modified both by the η_i coefficients and by the presence of new physics (exotic particles in loops, etc.).



Higgs-Photon Coupling:

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

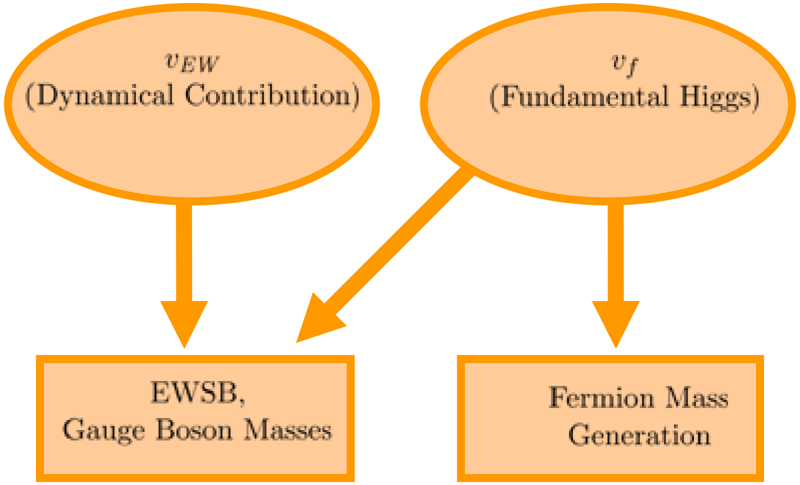
Higgs-Gluon Coupling:

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

- 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.

Scenario 1: Suppressed h!γγ

- Consider an additional contribution v_{EW} to EWSB that does not contribute to fermion mass generation. It may or may not be associated with additional light Higgs doublets Φ^i_{EW}.
- Fermion masses result from the Yukawa interactions of the usual fundamental Higgs boson Φ_f.
- This is an example of a Type I two Higgs doublet model.



v_{EW}
(Dynamical Contribution)

v_f
(Fundamental Higgs)

EWSB,
Gauge Boson Masses

Fermion Mass
Generation

η Parameters

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

Mixing Angles

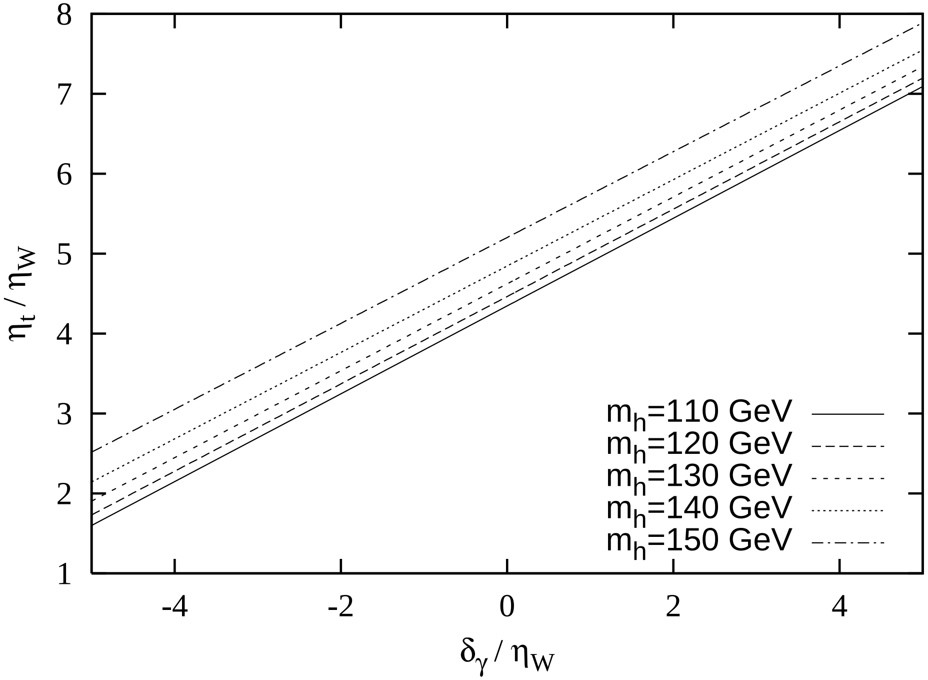
$$\tan\beta = \frac{v_f}{v_{EW}} \qquad \begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \sqrt{2}\mathrm{Re}(\Phi^0_{EW}) \\ \sqrt{2}\mathrm{Re}(\Phi^0_f) \end{pmatrix}$$

Fermion-Boson Loop Interference

- $h\gamma\gamma$ 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.

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

Quashed effective hγγ vertex!



- For a light (115 GeV $\lesssim m_h \lesssim$ 150 GeV) Higgs, only an $\mathcal{O}(1)$ shift in η_t/η_W is required for drastic suppression.
- For small α, this corresponds to $\sin\beta \sim 0.45$.
- For any $|\alpha| \lesssim 1/2$, the result is qualitatively the same.

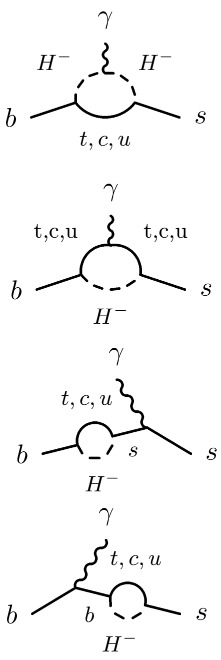
$$\eta_f > 1 \qquad \eta_{W,Z} < 1$$

Limits on Higgs Mixing

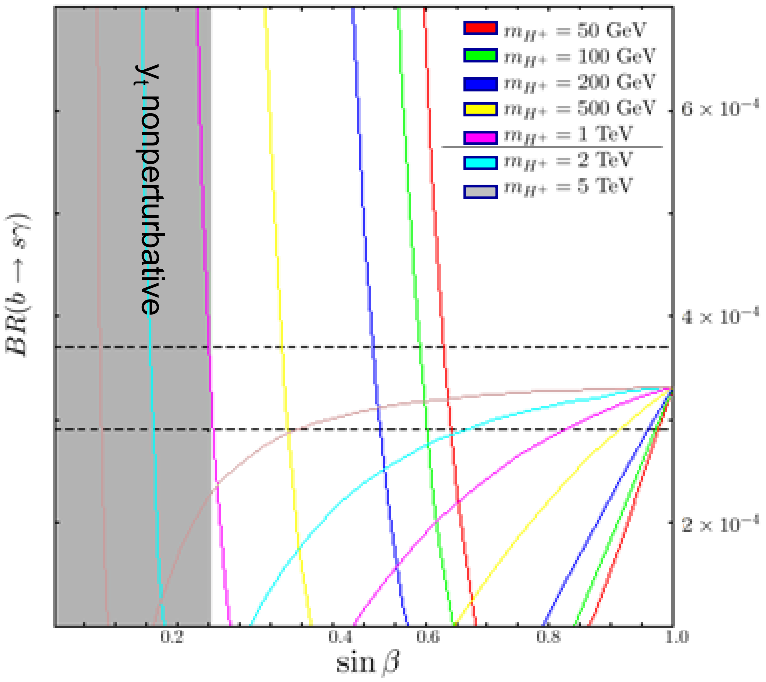
- The requirement that the top quark Yukawa coupling be perturbative places a lower bound on $\sin\beta$:

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

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



Constraints from $b\to s\gamma$



- The most stringent experimental limit is from $b\to s\gamma$. The combined bound from CLEO and Belle is $BR(b\to s\gamma) = ((3.3\pm0.4)\times10^{-4}$.
- The charged Higgs contribution can interfere with the SM amplitude.
- When $m_{H^\pm} \gtrsim$ (afewTeV), all $\sin\beta$ allowed by top perturbativity are permitted.
- Other (weaker) bounds exist from $K_L - K_S$ and $B^0 - \overline{B}^0$ mixing.

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.

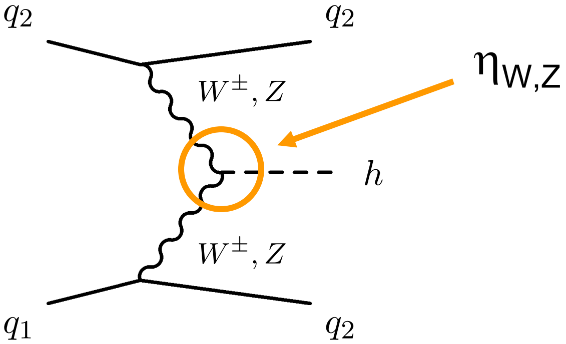
3). Modification of Total Higgs Width

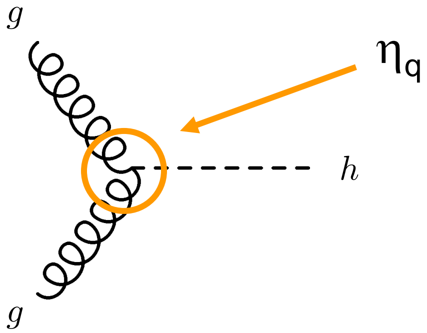
$$\frac{\sigma_h(\gamma\gamma)}{\sigma_h(\gamma\gamma)_{sm}} = \frac{\Gamma_h(gg)}{\Gamma_h(gg)_{sm}} \frac{\Gamma_h(\gamma\gamma)}{\Gamma_h(\gamma\gamma)_{sm}} \left(\frac{\Gamma_h(\text{tot})}{\Gamma_h(\text{tot})_{sm}}\right)^{-1}$$

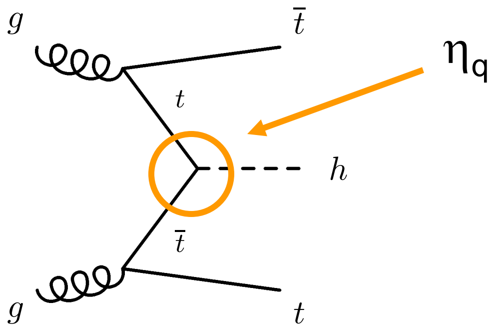
1). Modification of Production Cross Section

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)



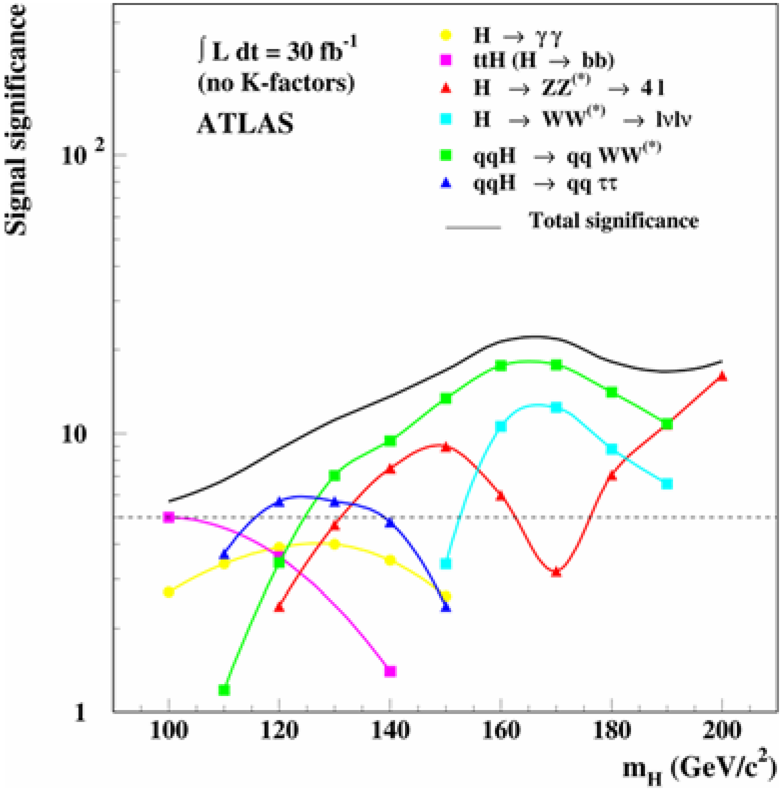




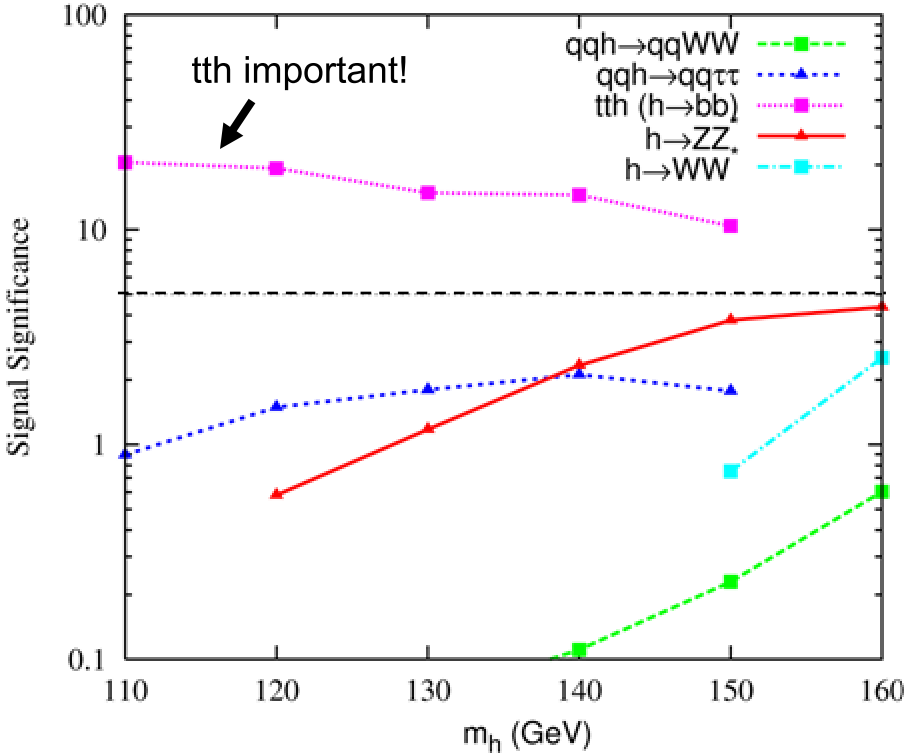
Significance of Discovery

- 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



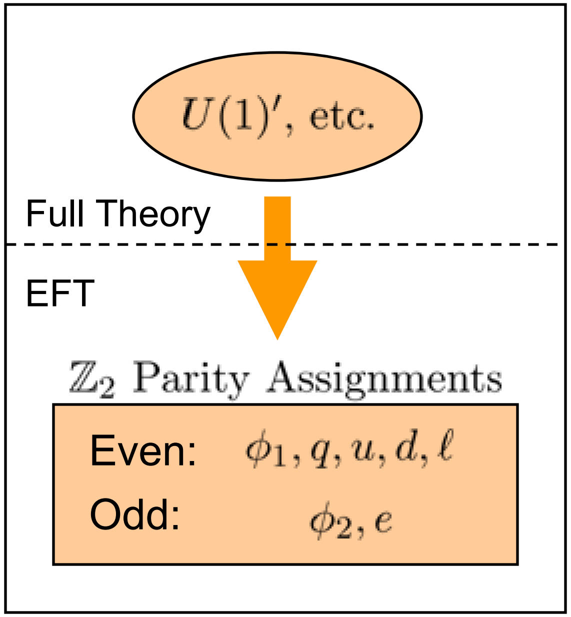
Two-Photon Decay Suppressed



tth important!

Scenario II: "Lepton-Specific Higgs"

- Consider a 2HDM in which one Higgs ϕ_q couples exclusively to (up- and down-type) quarks, the other ϕ_ℓ exclusively to leptons (Type IV Higgs).



$U(1)'$, etc.

Full Theory

EFT

$\mathbb{Z}_2$ Parity Assignments

Even:	ϕ_1, q, u, d, ℓ
Odd:	ϕ_2, e

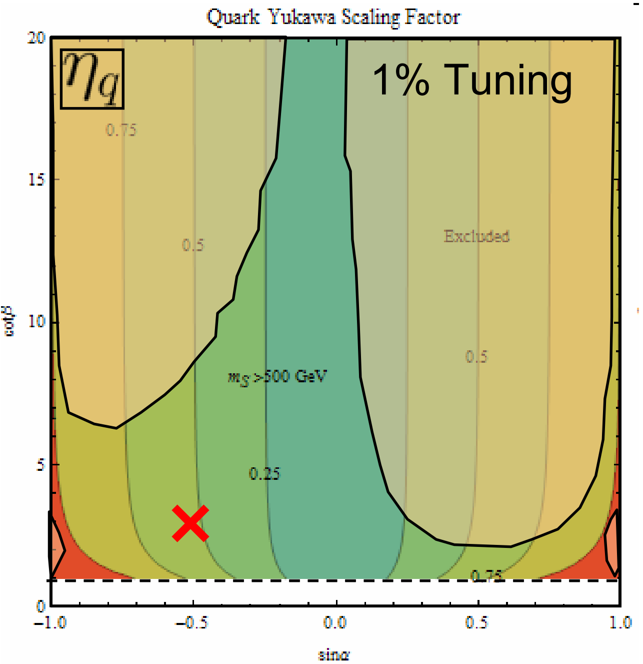
$$\tan\beta \equiv \frac{v_q}{v_\ell}$$

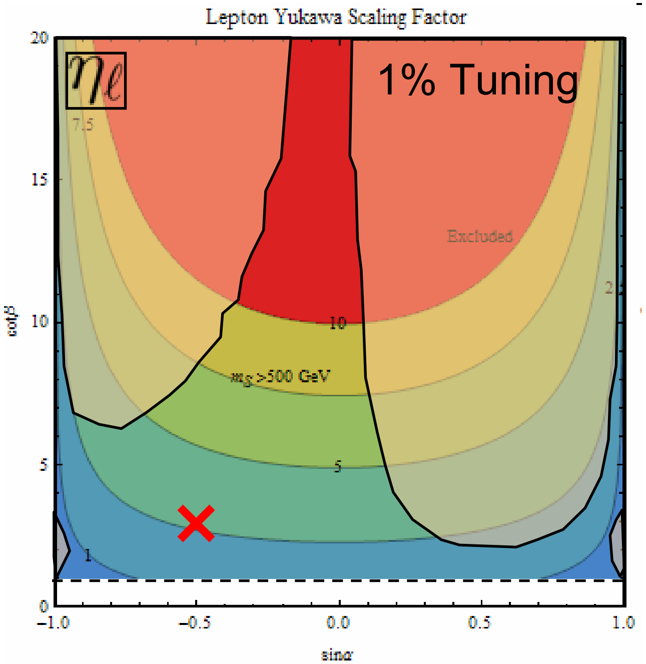
- We choose the point $\cot\beta = 3$, $\sin\alpha = -1/2$.

- EFT has a $\mathbb{Z}_2$ softly broken by a term $m_{12}^2(\phi_1^\dagger\phi_2 + h.c.)$.

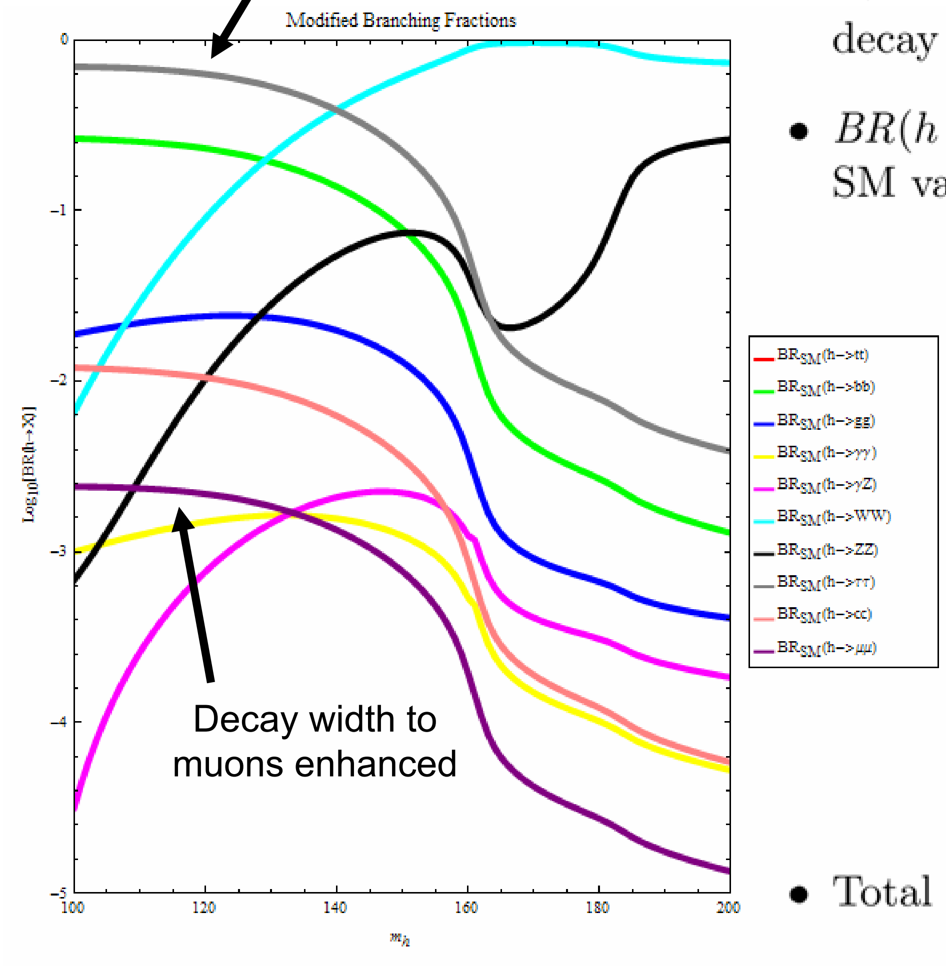
$$\eta_q = -\frac{\sin\alpha}{\cos\beta} \qquad \eta_\ell = \frac{\cos\alpha}{\sin\beta} \qquad \eta_{W,Z} = \sin(\beta-\alpha)$$

- Enforce $m_A, m_{H^0}, m_{H^\pm} \geq 500$ GeV and relative tuning of at most 1%.





Widths and Branching Ratios

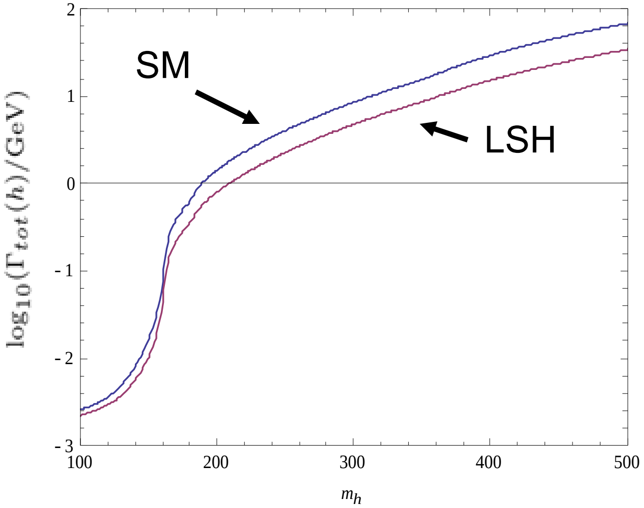


Decay width to taus dominates!

Decay width to muons enhanced

- For 115 GeV $\lesssim m_h \lesssim$ 130 GeV, the dominany Higgs decay channel is into $\tau\overline{\tau}$.
- $BR(h \to \mu\overline{\mu})$ is significantly increased relative to its SM value.

Total Higgs Width

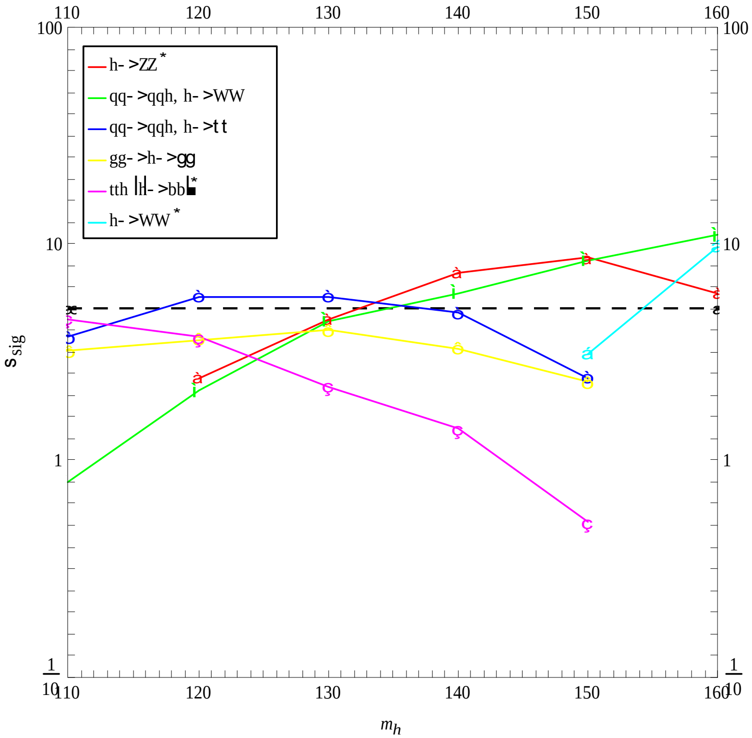


- Total Higgs width similar to that in the SM.

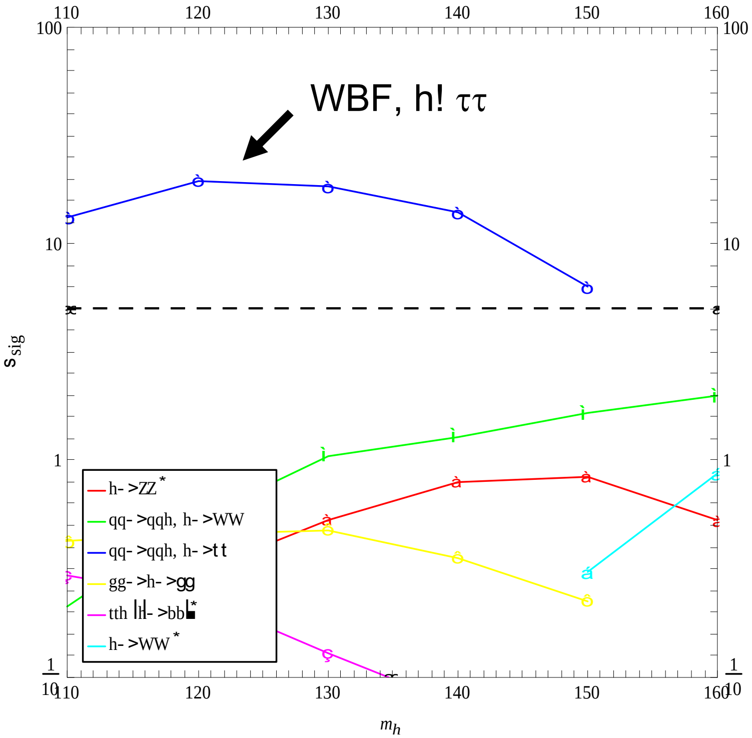
The Usual Discovery Channels

- The small η_q reduces both $hq\bar{q}$ and hgg effective couplings, while weak boson fusion is only slightly suppressed.
- For this choice of parameters, the weak boson fusion process $qq \to qqh(h \to \tau\tau)$ becomes the most important discovery channel.

Standard Model Higgs



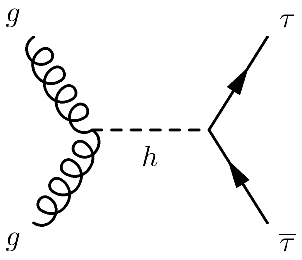
“Lepton-Specific Higgs”



The Unusual Discovery Channels

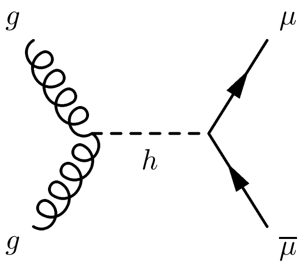
- We have chosen a particular α and β here, but the allowed parameter space has a rich variety of phenomenological possibilities.

- In regions of parameter space where η_q (and hence η_g) is not drastically suppressed, “new” discovery channels can open up:



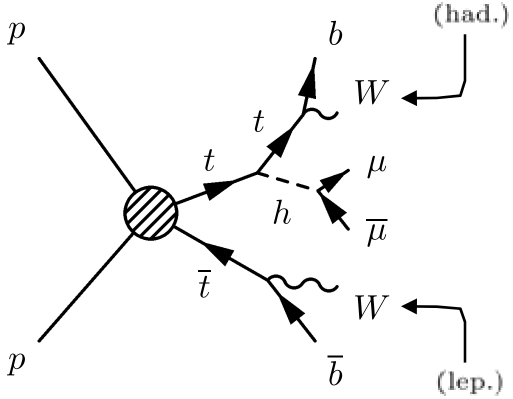
$gg \to h \to \tau\bar{\tau}$

(Several Authors)



$gg \to h \to \mu\bar{\mu}$

(Han & McElrath, etc.)



$pp \to tth(h \to \mu\bar{\mu})$

- Processes involving Higgs decays to $\mu\bar{\mu}$ can become statistically interesting (Su & Thomas, in progress).

Conclusions

- EWSB may be a complicated process involving contributions from several sources, even when the effective theory contains one light Higgs.
- Couplings between h and other fields may differ drastically from those of the SM. This can have a dramatic effect on collider observables at the LHC.
- In type-I Higgs models, the $gg \to h \to \gamma\gamma$ cross-section may be highly suppressed. In this case, $t\bar{t}h(h \to b\bar{b})$ becomes by far the most important discovery channel for for a light Higgs.
- In models where different doublets are responsible for the masses of quarks and leptons, leptonic Higgs decay channels can become far more significant than in the SM.

Acknowledgments

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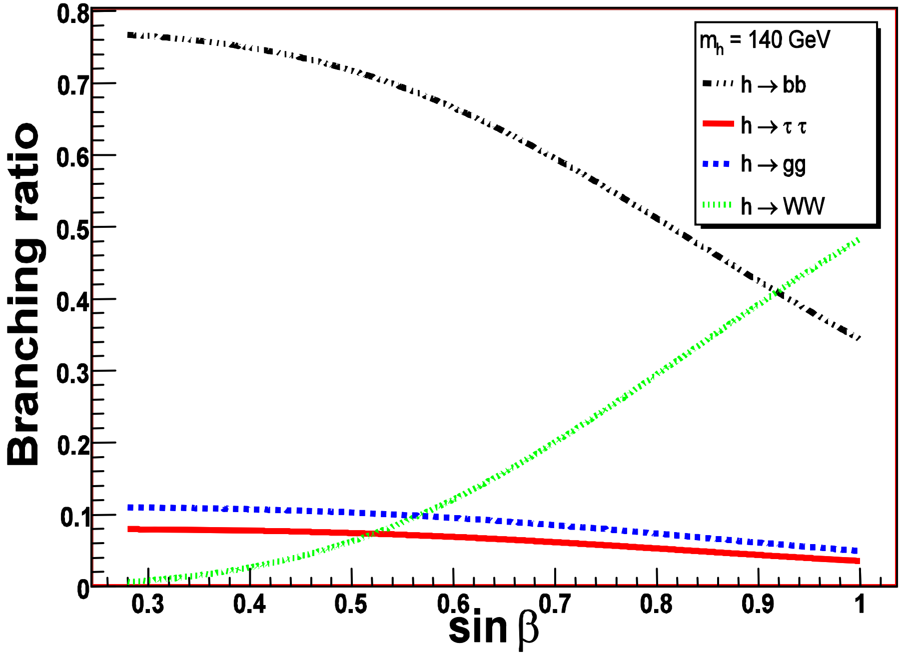
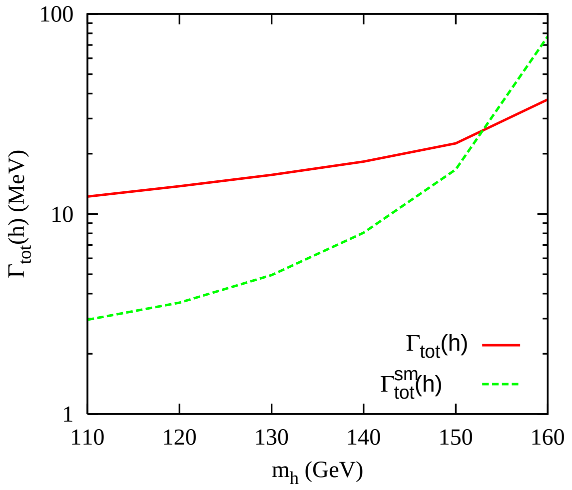
Extra Slides

The Effect on Branching Fractions

- When 100 GeV $\lesssim m_h \lesssim$ 135 GeV, Higgs decays are primarily fermionic and hence enhanced by η_f relative to the SM.
- When 135 GeV $\lesssim m_h \lesssim$ 150 GeV, Higgs decays are primarily bosonic and hence suppressed.
- 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 SM width. As a result, branching fractions are suppressed.



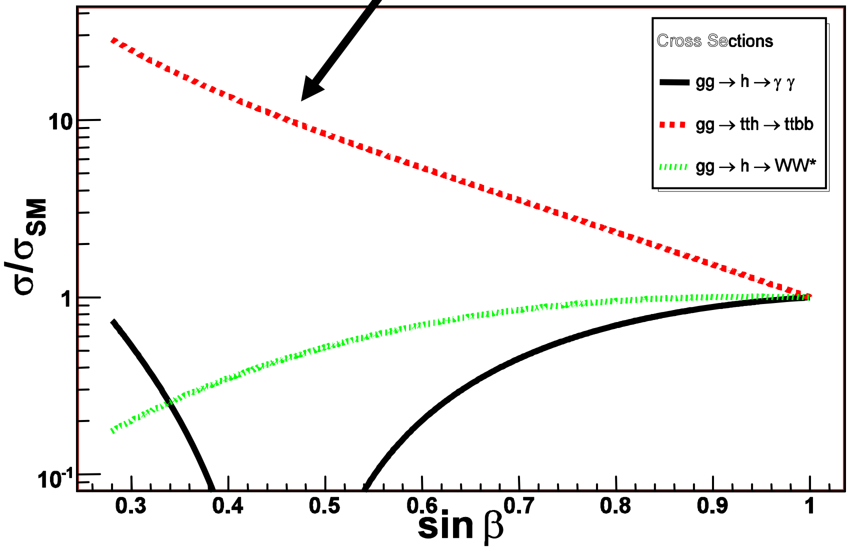
Total Higgs Width



m_h=140 GeV α=0

The Effect on Observables

- In this scenario, $t\bar{t}h$ processes withthe Higgs decaying to fermions ($b\bar{b}$, $\tau\bar{\tau}$) are significantly enhanced.
- All other relevant discovery channels are suppressed!
- 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.



Dramatic Increase over SM!

- This means that the significance of discovery in each channel can be obtained from scaling up the SM significance by the same factor that multiplies the associated observable.