Leptophilic Higgs Signatures at the LHC

(And the Importance of Leptonic Decays for Higgs Discovery)

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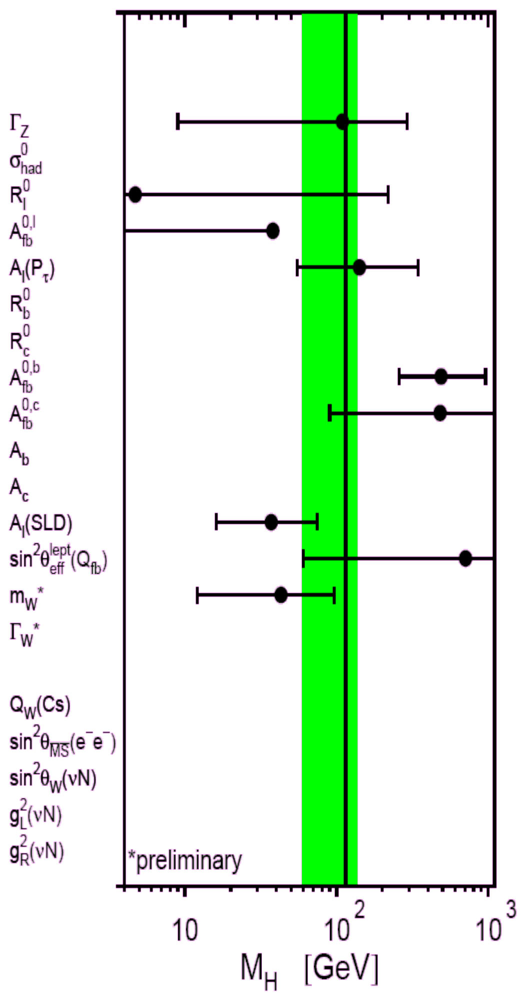
Shufang Su & BT [arXiv:0903.0667]

What do we know about EWSB?

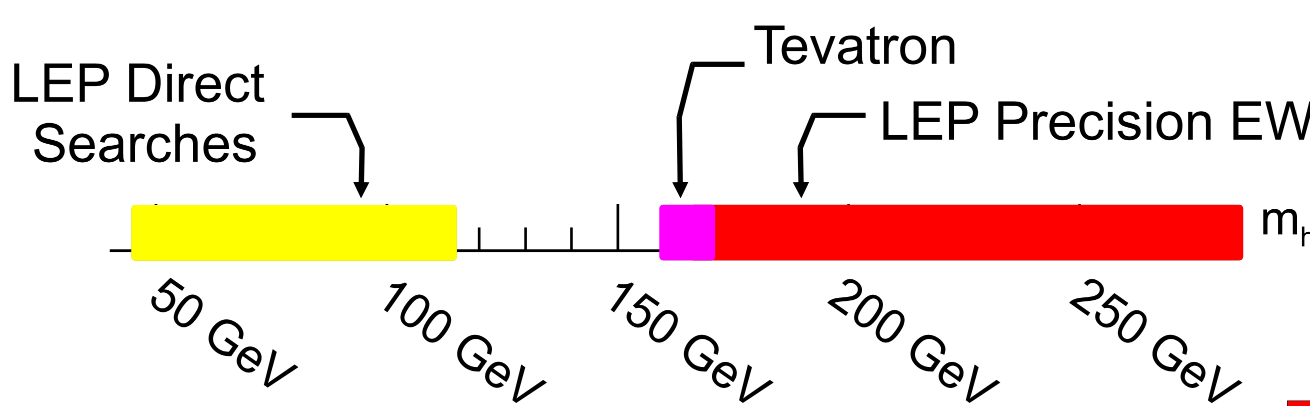
- Not Much. We don't yet know how EWSB works or how many effects contribute.



- Experimental data are still consistent with the SM description of EWSB (i.e. one Higgs doublet), but the window for the Higgs mass is shrinking.

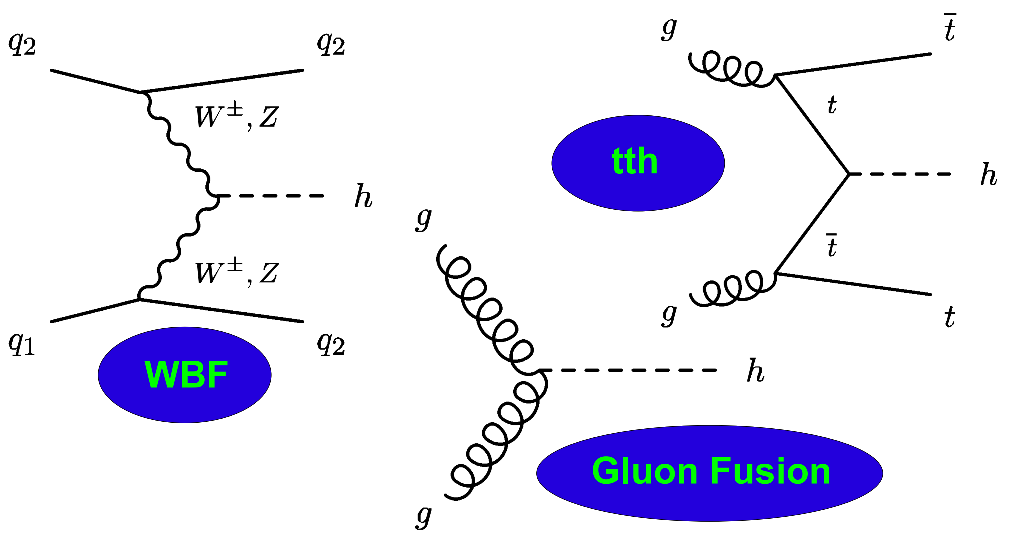
- Considerations related to naturalness and the Hierarchy problem suggest that the SM should be regarded as an effective description of some high-energy theory.

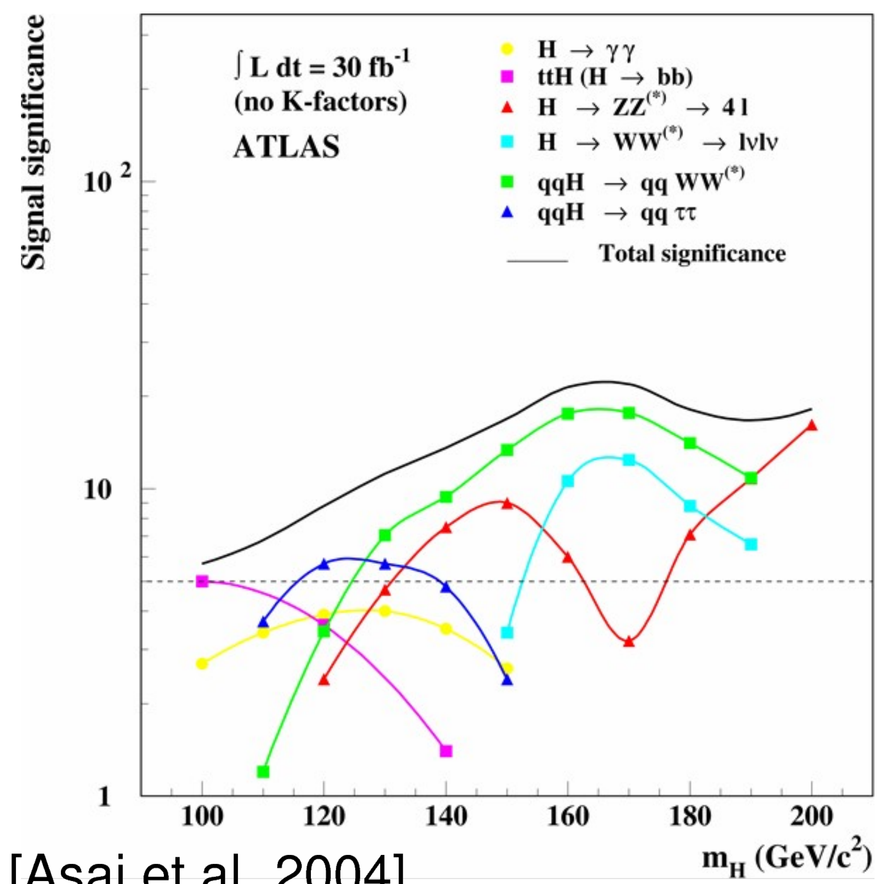
- One of the primary missions of the LHC (pp at $\sqrt{s} \approx 14$ GeV) is to alleviate our ignorace about EWSB.



Detecting a SM Higgs at the LHC

- For a light Higgs (115 GeV $\lesssim m_h \lesssim 140$ GeV), the particularly promising discovery channels are:
- $gg \to h \to \gamma\gamma$ is useful due to its low invariant mass resolution; $h \to WW^*$ and $h \to ZZ^*$ important when $m_h \gtrsim 130$ GeV.
- Weak boson fusion processes are also significant.
- tth processes, though important for lighter Higgs, are not terribly important in this mass range.





[Asai et al. 2004]

Many Paths to One Light Higgs

- Let us focus on models that are "Standard Model-like" in that the weak-scale EFT contains one (and only one) light Higgs boson.

Examples

- SUSY (in the decoupling limit)
- General 2HDM (or 3HDM, etc.)
- Certain dynamical EWSB models
- Many other possibilities

- The properties of a light Higgs in these scenarios can differ radically from those expected in the SM.
- Leads to unusual signature patterns at the LHC.

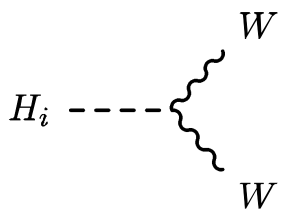
The point is that many models lead to EFTs that roughly resemble the SM, but can be distinguished by patterns of light Higgs observables.

[cf. Barger, Logan, and Shaughnessy 2009]

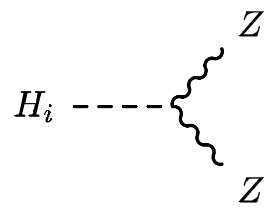
Effective Couplings from Non-Minimal Higgs Sectors

- In multi-Higgs models, the couplings of a Higgs boson to WW and ZZ are proportional to that Higgs' 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 SM 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 parameterize them using coefficients $\eta_{W,Z}$ and η_{f_i} [Phalen, BT, Wells].

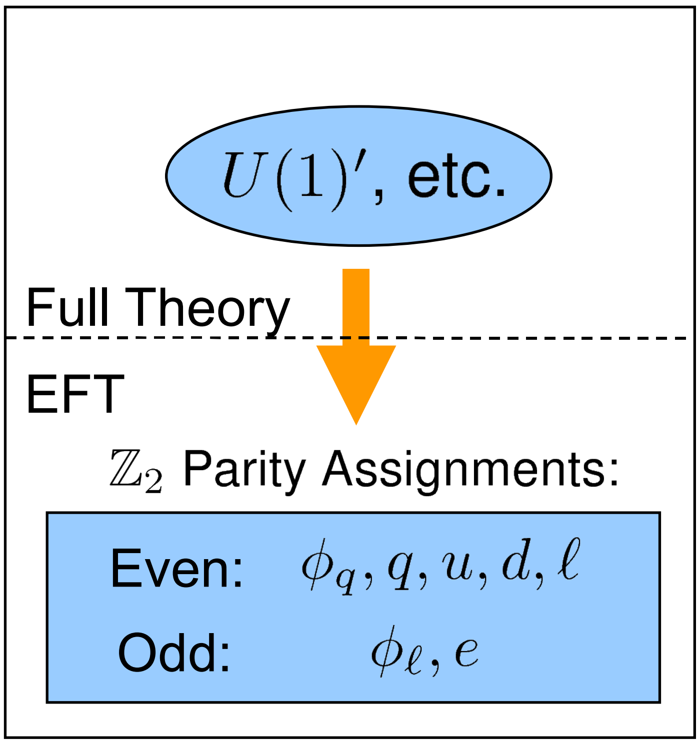
$$g_{hWW} = \eta_{W,Z}\, g^{sm}_{hWW} \qquad g_{hZZ} = \eta_{W,Z}\, g^{sm}_{hZZ} \qquad g_{hf\bar{f}} = \eta_f\, g^{sm}_{hf\bar{f}}$$

Generally not universal

A Leptophilic Higgs

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

$$\mathcal{L}_{Yuk} = -(y_u)_{ij}\overline{Q}_i\phi_q^c u_j - (y_d)_{ij}\overline{Q}_i\phi_q d_j - (y_\ell)_{ij}\overline{L}_i\phi_\ell e_j + h.c.$$



- We consider the most general, potential consistent with gauge symmetries, CP conservation, and an additional $\mathbb{Z}_2$ parity.

Higgs Potential

$$\begin{aligned} V \;=\; & \lambda_1|\phi_q^\dagger|^4 + \lambda_2|\phi_\ell|^4 + \lambda_3|\phi_q|^2|\phi_\ell|^2 \\ & + \lambda_4|\phi_q^\dagger\phi_\ell|^2 + \frac{\lambda_5}{2}\left[(\phi_q^\dagger\phi_\ell)(\phi_q^\dagger\phi_\ell) + h.c.\right] \\ & + m_1^2|\phi_q|^2 + m_2^2|\phi_\ell|^2 \ldots + \underbrace{m_{q\ell}^2\phi_q^\dagger\phi_\ell + h.c.}_{\mathbb{Z}_2 \text{ Violating}} \end{aligned}$$

- The $\mathbf{Z}_2$ symmetry is broken only softly, by an additional mass term which couples ϕ_q and ϕ_ℓ.

Why look at unusual possibilities?

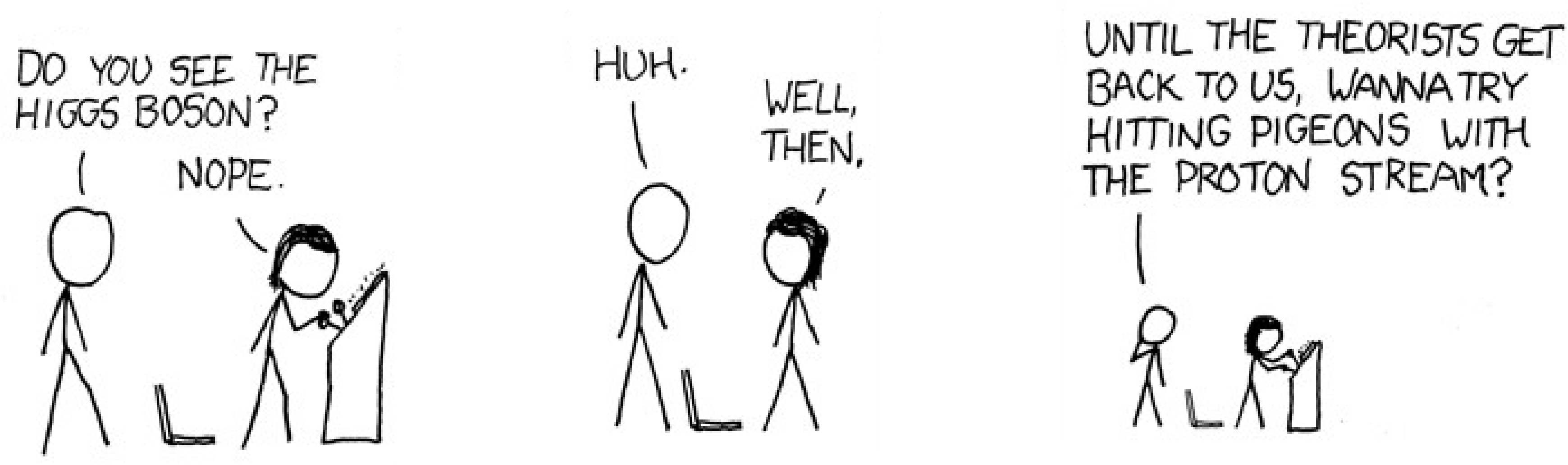
1). We don't want to "miss" a light Higgs.

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

[Barger, Hewett, Phillips 1990]   [Barger, Logan, Shaughnessy 2009]

3). Other motivations (dark matter detection, neutrino physics, etc.):

[Goh, Hall, Kumar 2009]   [Aoki, Kanemura, Seto 2008]



[cartoon from xkcd.com]

Coupling Modifications

- In a 2HDM, as in the MSSM, masses and mixings in the Higgs sector can be written in terms of the two mixing angles α and β.

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

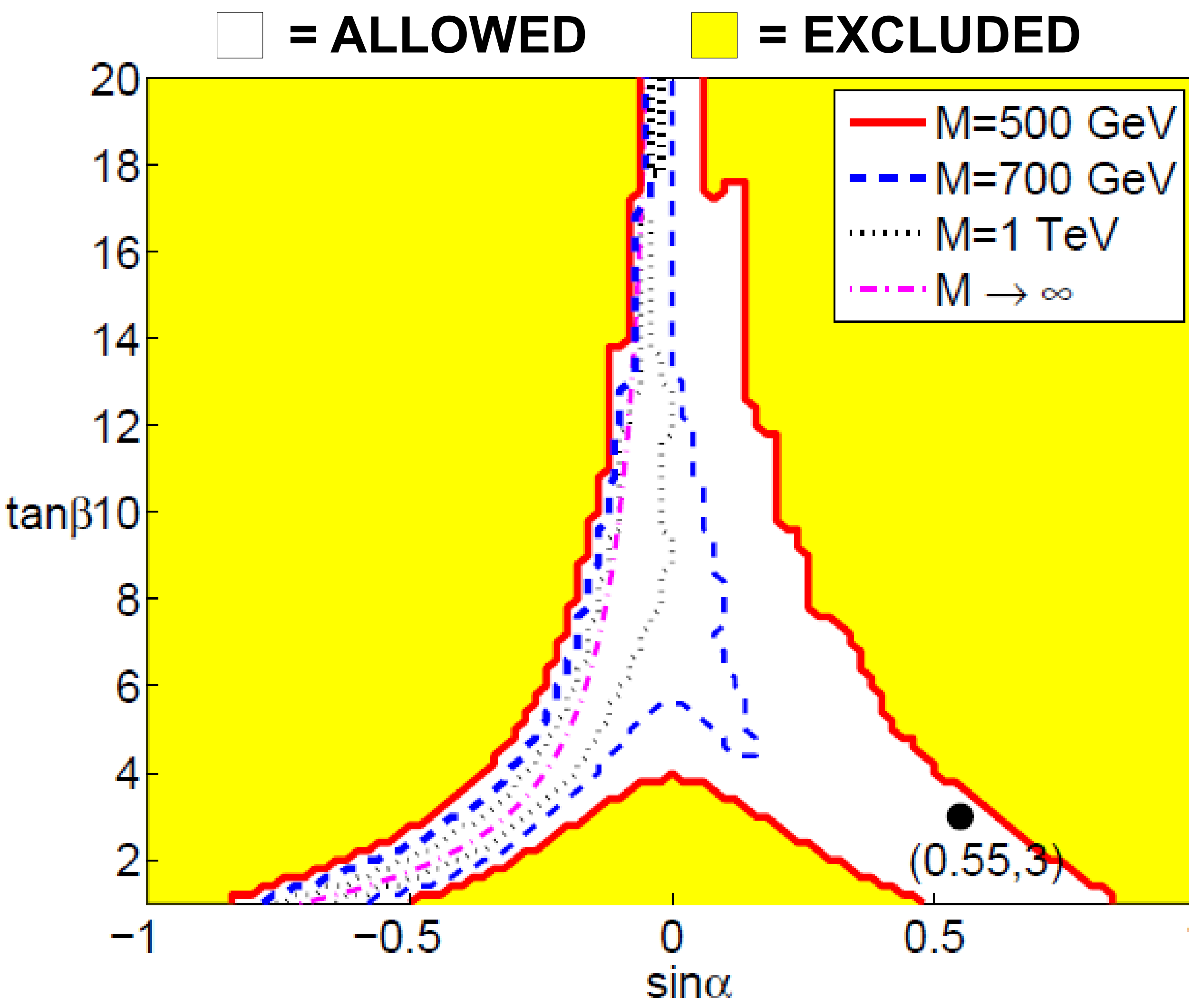
$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re}[\phi_q - v_q] \\ \mathrm{Re}[\phi_\ell - v_\ell] \end{pmatrix}$$

CP-even (h, H^0) **CP-odd** (A)

Physical Scalars: $h,\quad H^0,\quad A,\quad H^\pm$

- We will be interested in situations in which only h is light enough to be easily detected at the LHC.
- One such situation occurs in the strict decoupling limit, where $\alpha \approx \beta - \pi/2$ and $m^2_{H^0}, m^2_A, m^2_{H^\pm} \to \infty$.
- It is also interesting to examine for what range of **finite** $m^2_{H^0}$, m^2_A, and $m^2_{H^\pm}$ this criterion can be met in a healthy, consistent theory.

Consistency Conditions and Constraints:



We enforce...

- Vacuum stability at large field values.
- Perturbativity of all the λ_i.
- Tree-level unitarity of the S-matrix preserved.
- Pseudo-decoupling limit:

$$m_A, m_{H^\pm}, m_{H^0} > M$$

(for some high scale M)

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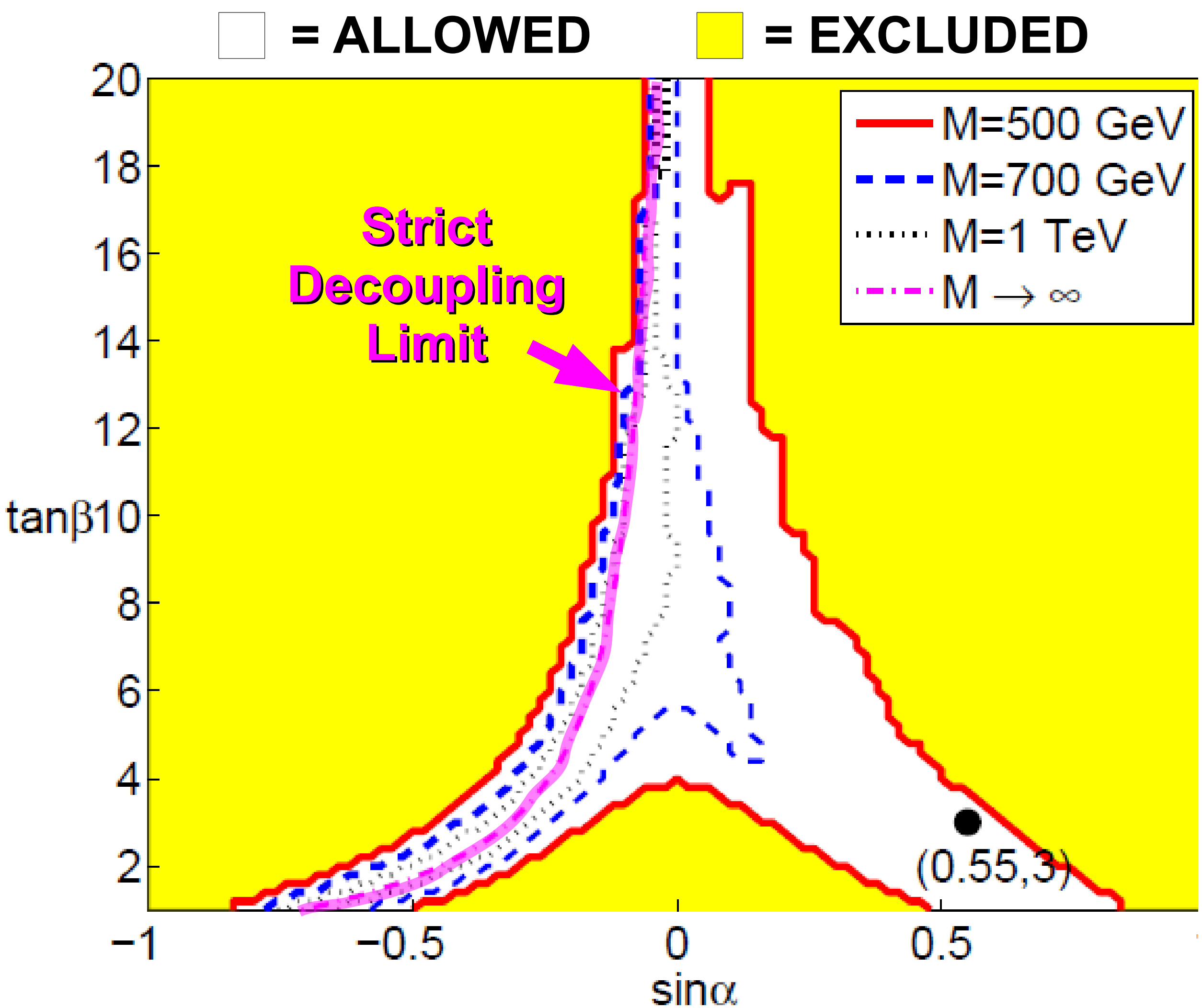

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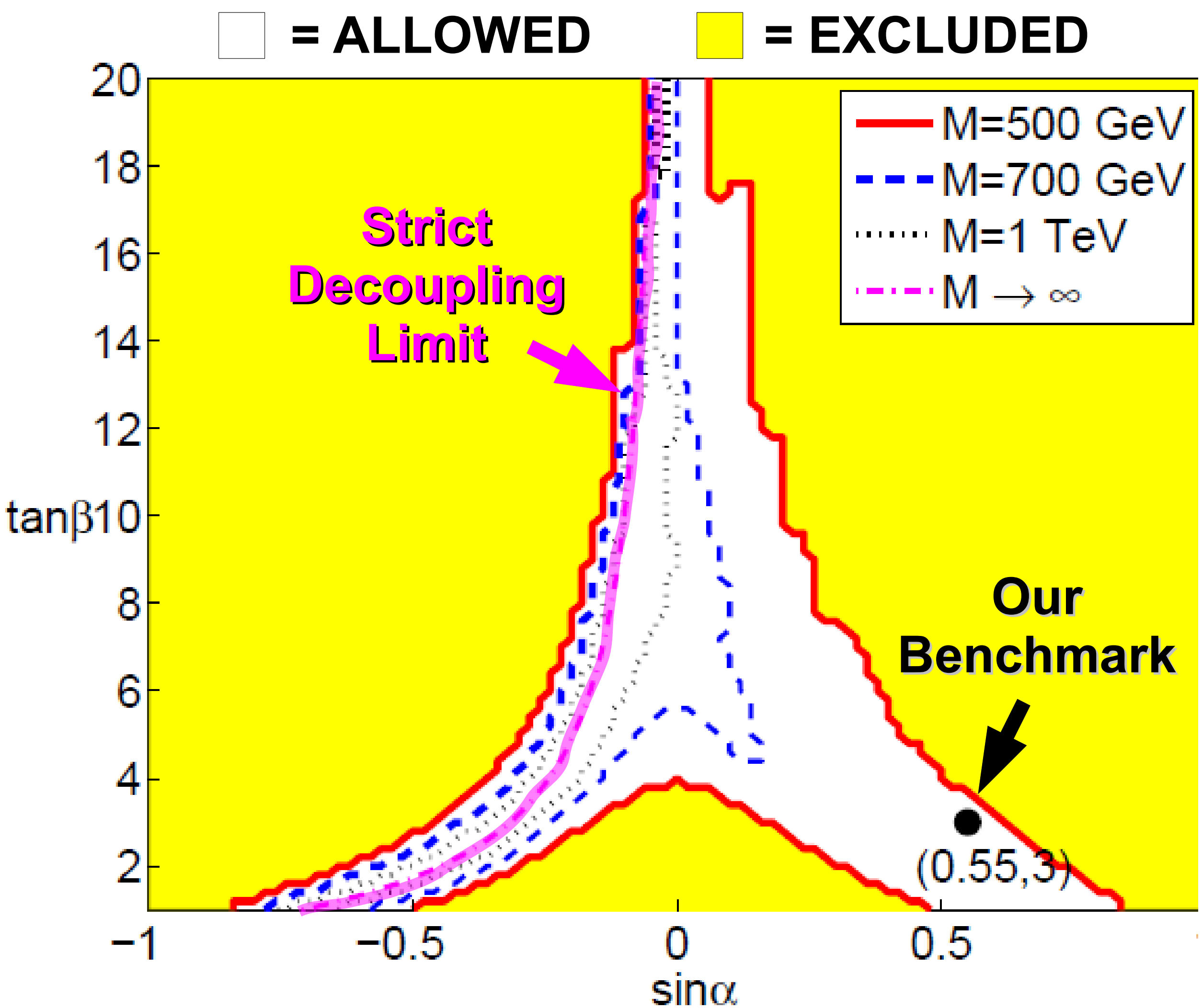

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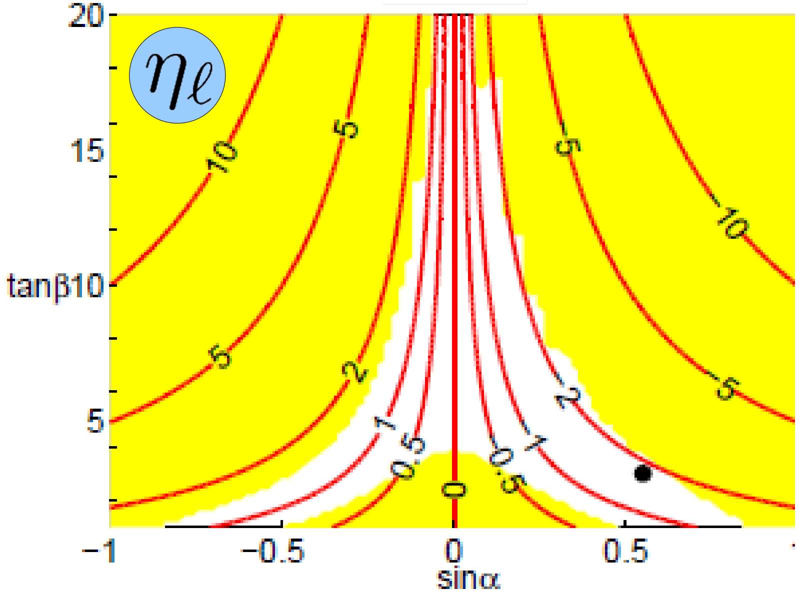
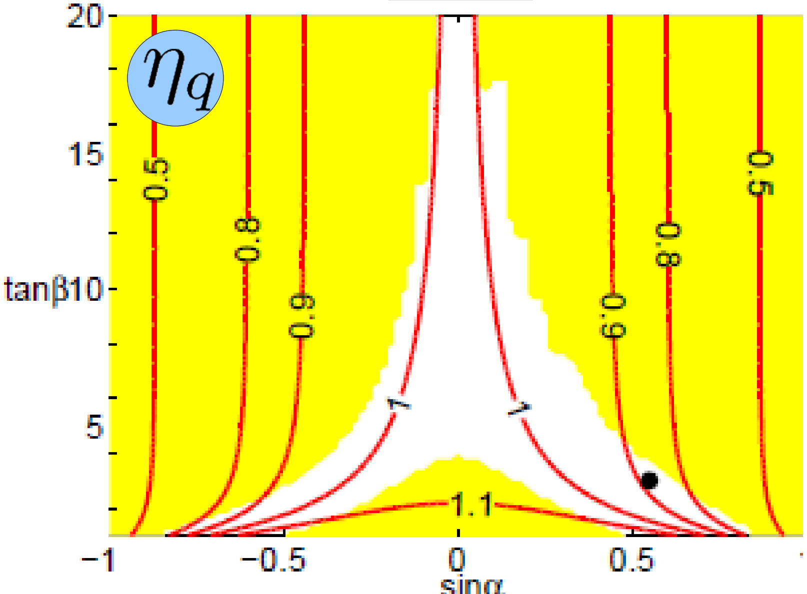
Coupling Modifications:

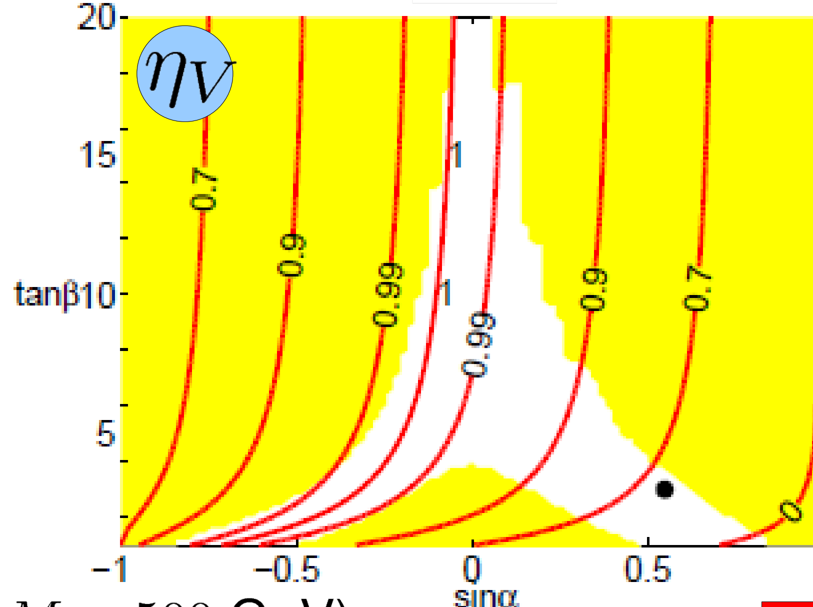
- In a 2HDM, the η parameters are determined solely by the angles α and β:

$$\eta_q = \frac{\cos\alpha}{\sin\beta} \qquad \eta_\ell = -\frac{\sin\alpha}{\cos\beta}$$

$$\eta_{W,Z} = \sin(\beta - \alpha)$$







(Exclusion regions shown: $M = 500$ GeV)

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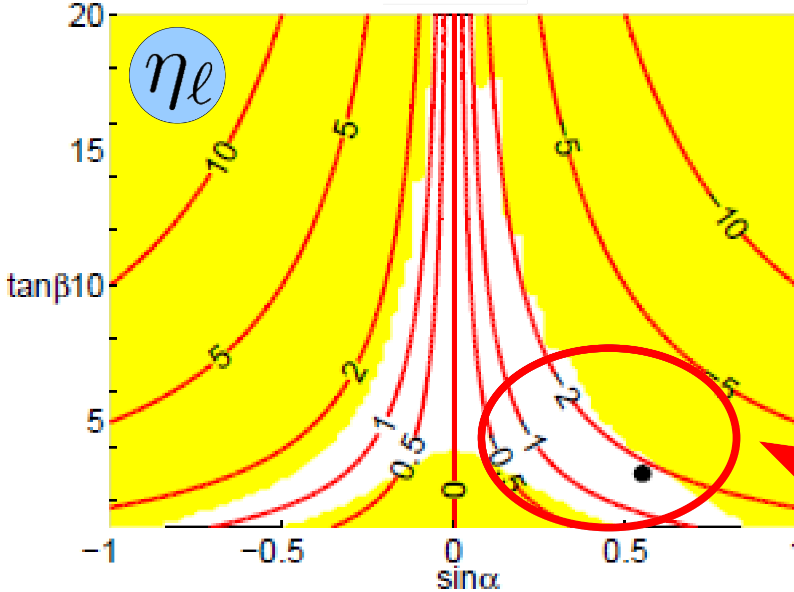
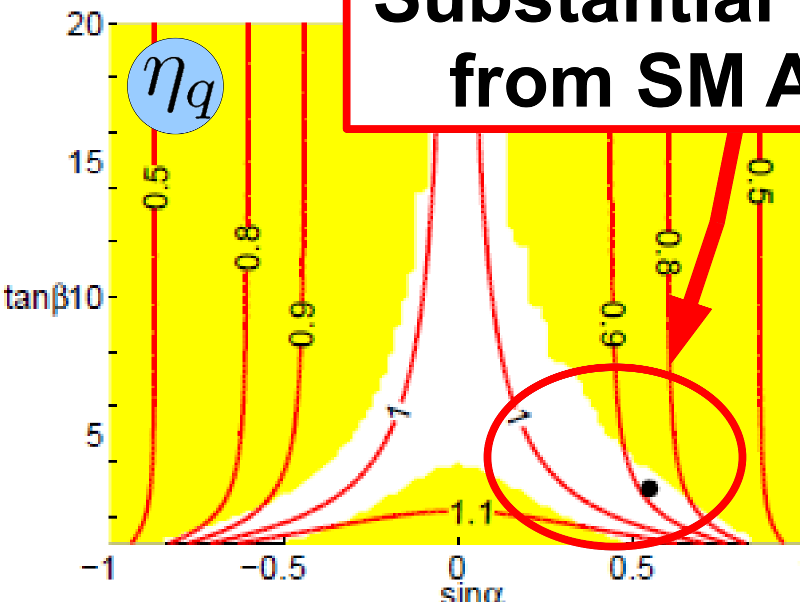


Substantial Deviations from SM Allowed!

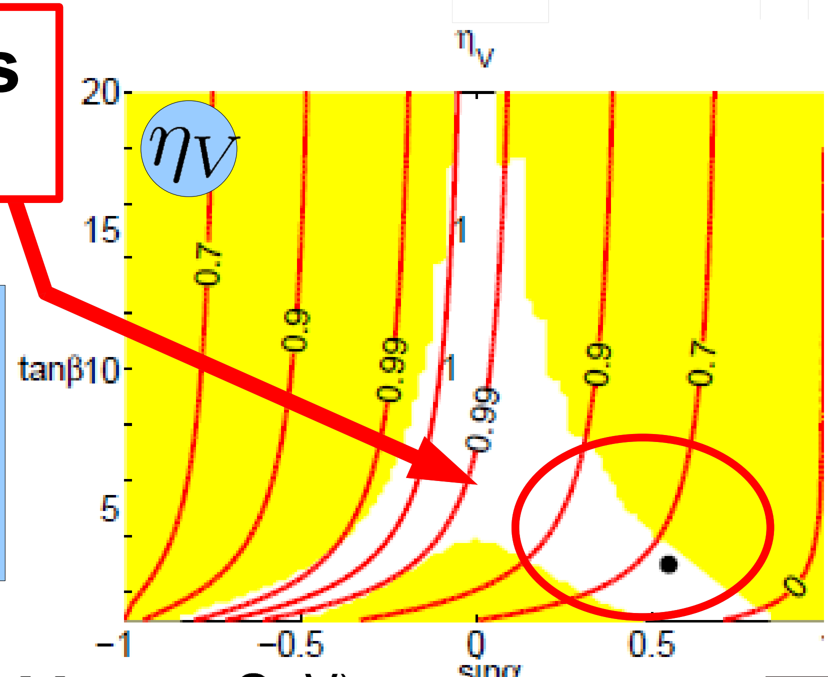


Benchmark:

$\eta_V = 0.62$

$\eta_q = 0.88$

$\eta_\ell = -1.74$



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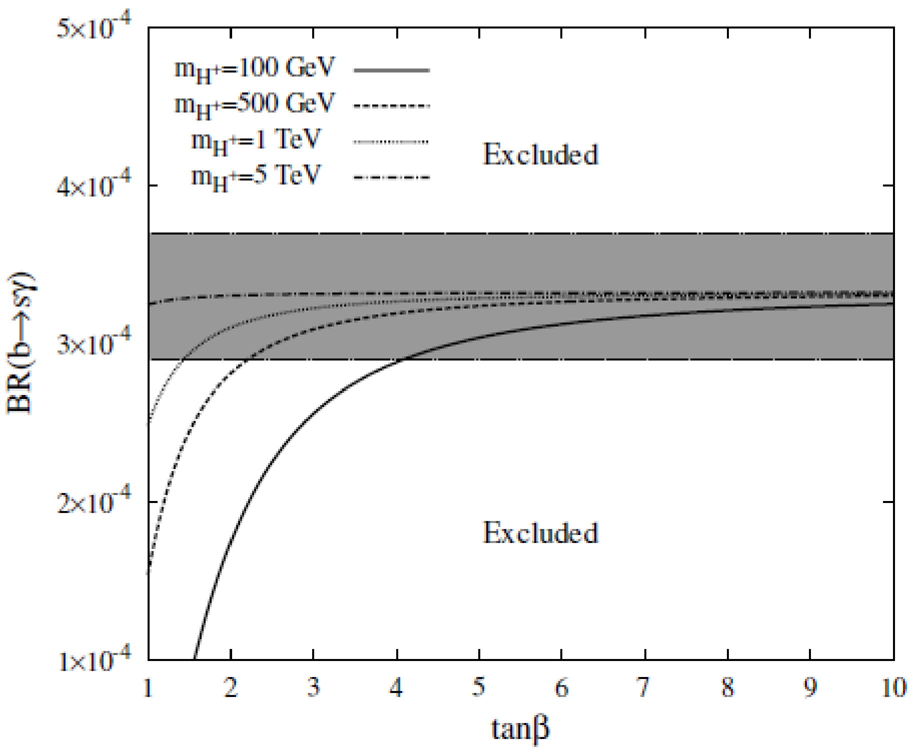
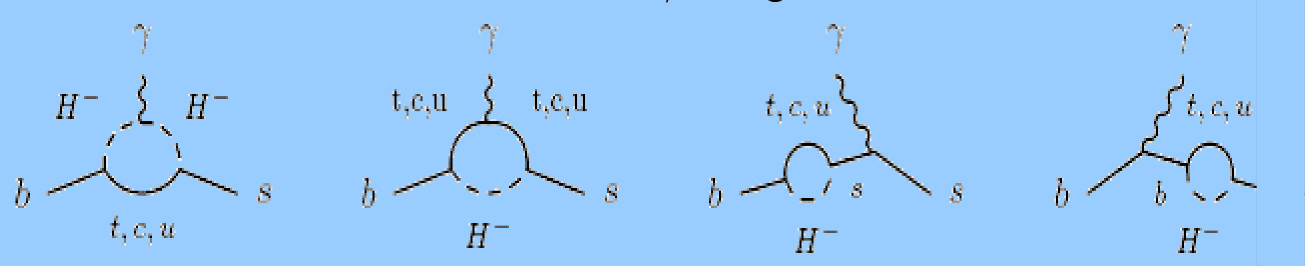
Flavor Violation Constraints

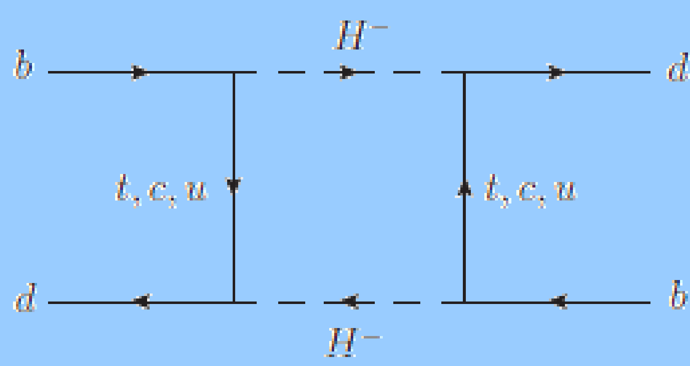


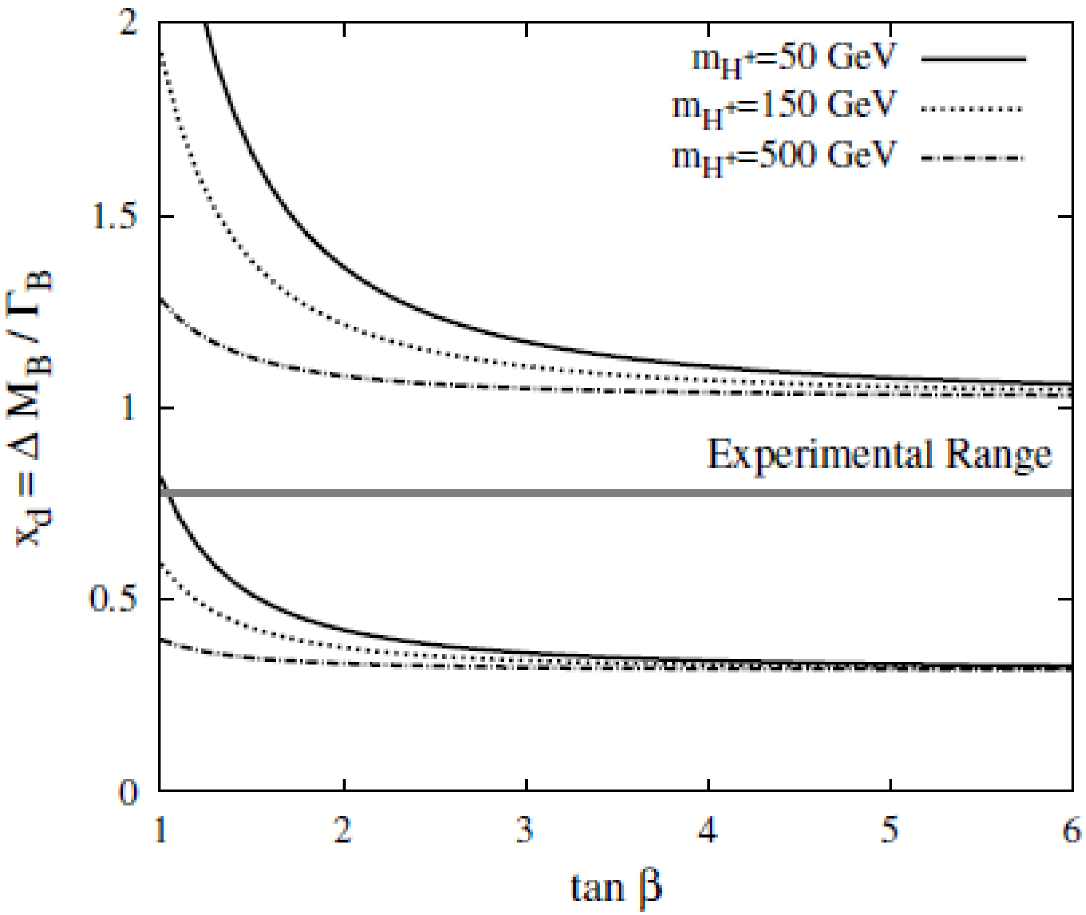
- Expertimental constraints on flavor violation must be satisfied, both in the hadron sector (e.g. $b \to s\gamma$, $B^0 - \overline{B}^0$ mixing) and the lepton sector (e.g. $\mu \to e\gamma$).
- Here, flavor-violating amplitudes in the hadronic sector are $\propto$ CKM mixing.
- $b \to s\gamma$ turns out to be the leading constraint.
- LFV processes are suppressed by inverse powers of the RH neutrino mass in see-saw models and are therefore not a problem.

$b \to s\gamma$ diagrams



$B^0 - \bar{B}^0$ mixing diagrams





- b-physics constraints are also easily satisfied
- Reason: $H^{\pm}qq'$ vertex **suppressed** by $\cot\beta$.

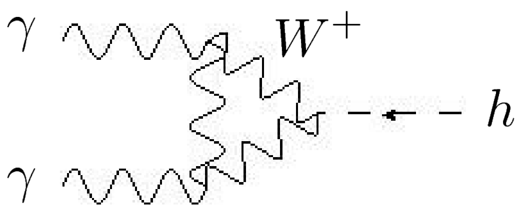
Large Theoretical Error Bars (bag factor, etc.)

Verdict: Experimental constraints ALSO satisfied.

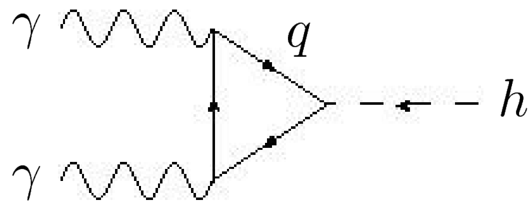
Effective Vertices:

- The η-factors for certain effective couplings arising at one loop are also of interest for collider phenomenology:

1. $h\gamma\gamma$:



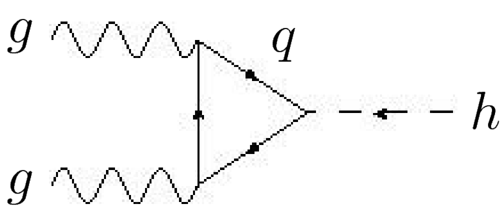
$+\sum_q$



$$\eta_\gamma = \frac{\eta_W F_1(\tau_W) + 3\sum_q Q_q^2 \eta_q F_{1/2}(\tau_q) + \sum_\ell \eta_\ell F_{1/2}(\tau_\ell)}{F_1(\tau_W) + 3\sum_q Q_q^2 F_{1/2}(\tau_q) + \sum_\ell F_{1/2}(\tau_\ell)}$$

2. hgg :

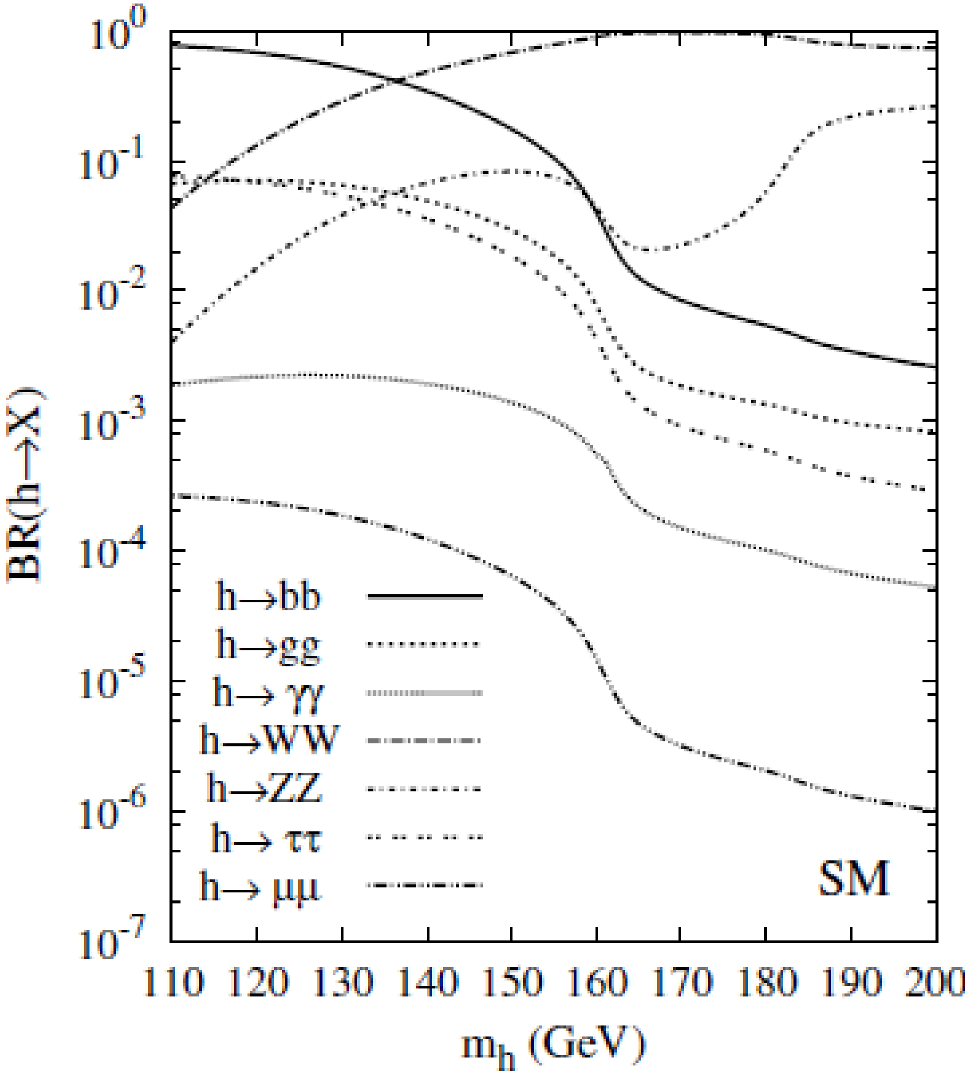
$\sum_q$



$$\eta_g = \frac{\sum_q \eta_q F_{1/2}(\tau_q)}{\sum_q F_{1/2}(\tau_q)} = \eta_q$$

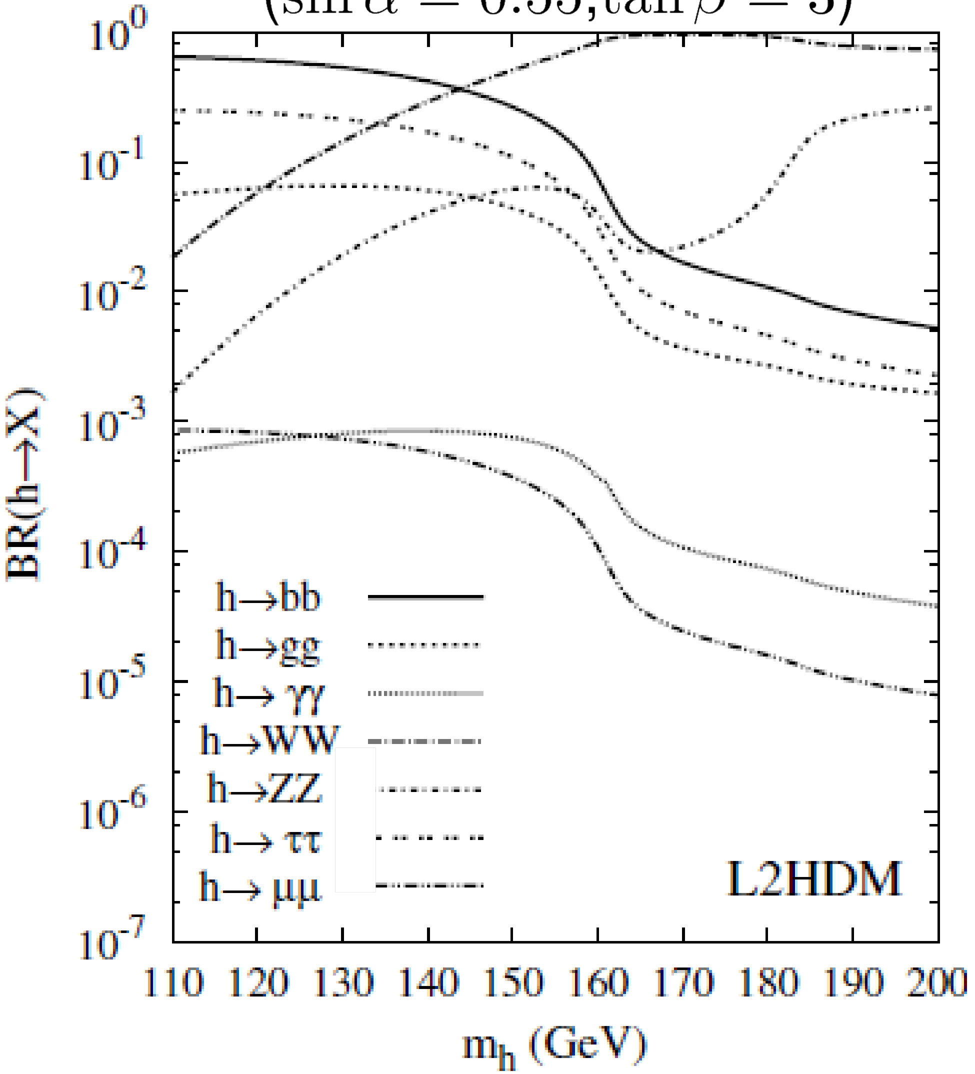
Higgs Branching Ratio Modifications

Standard Model



Leptophilic Model

$(\sin\alpha = 0.55, \tan\beta = 3)$



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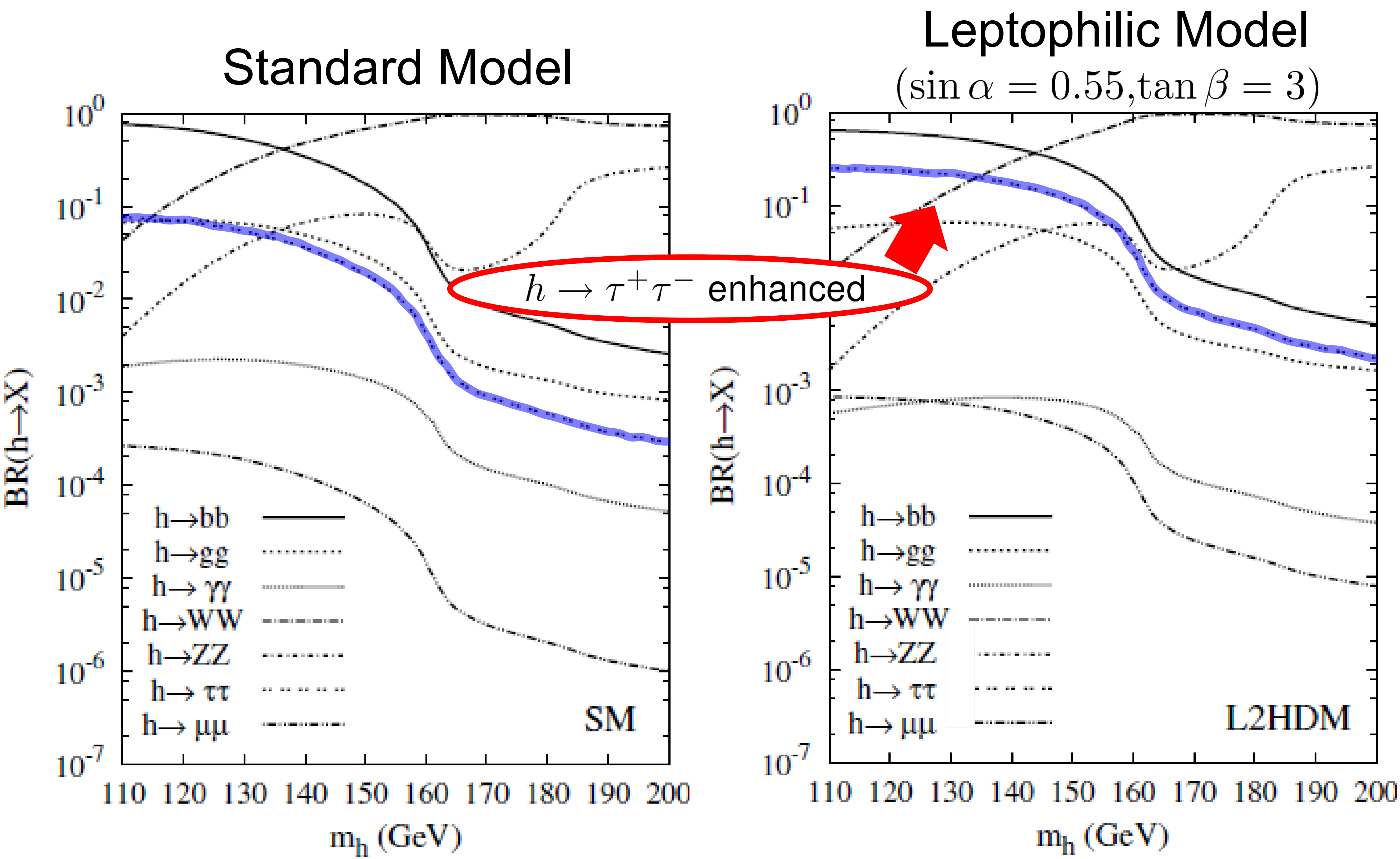

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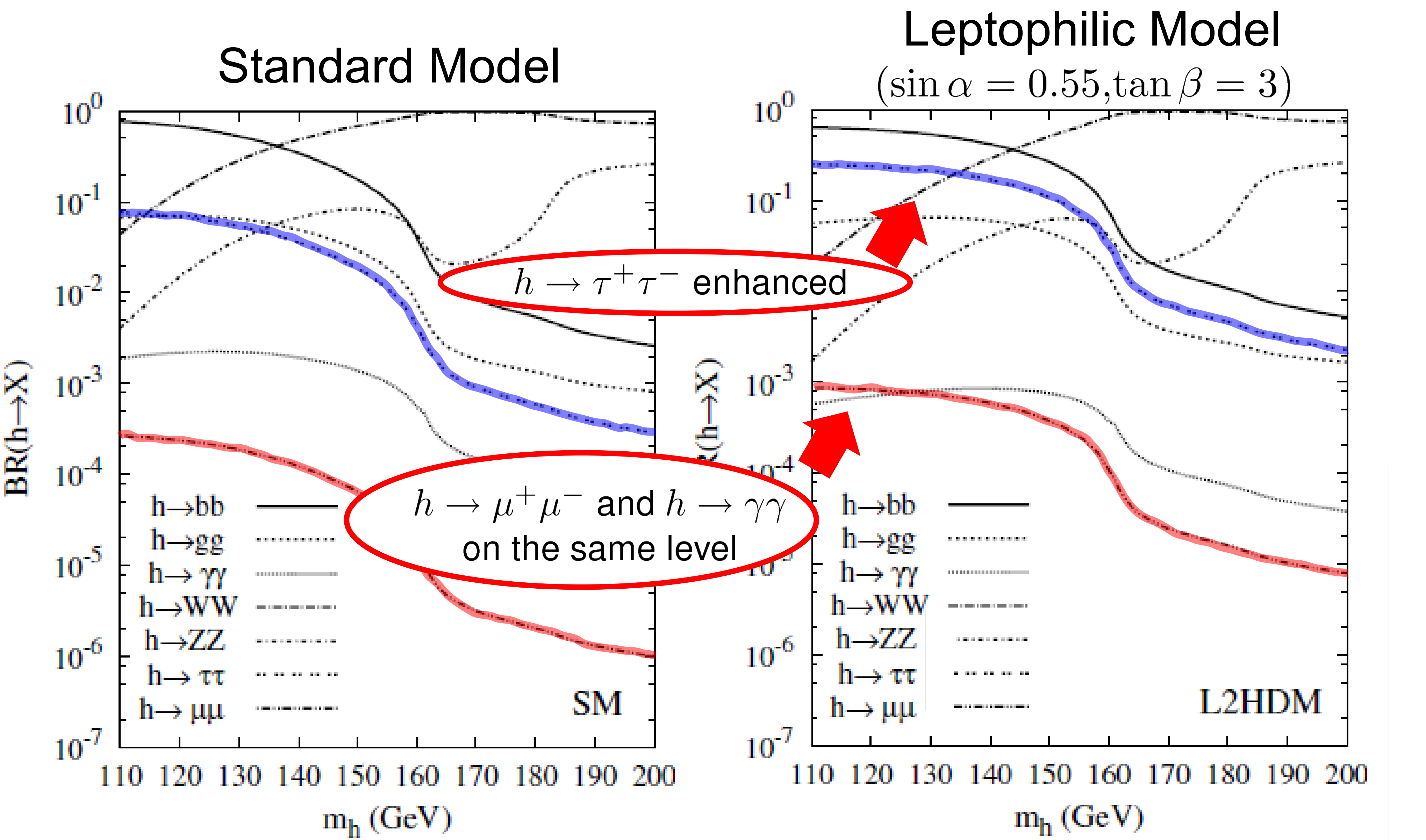
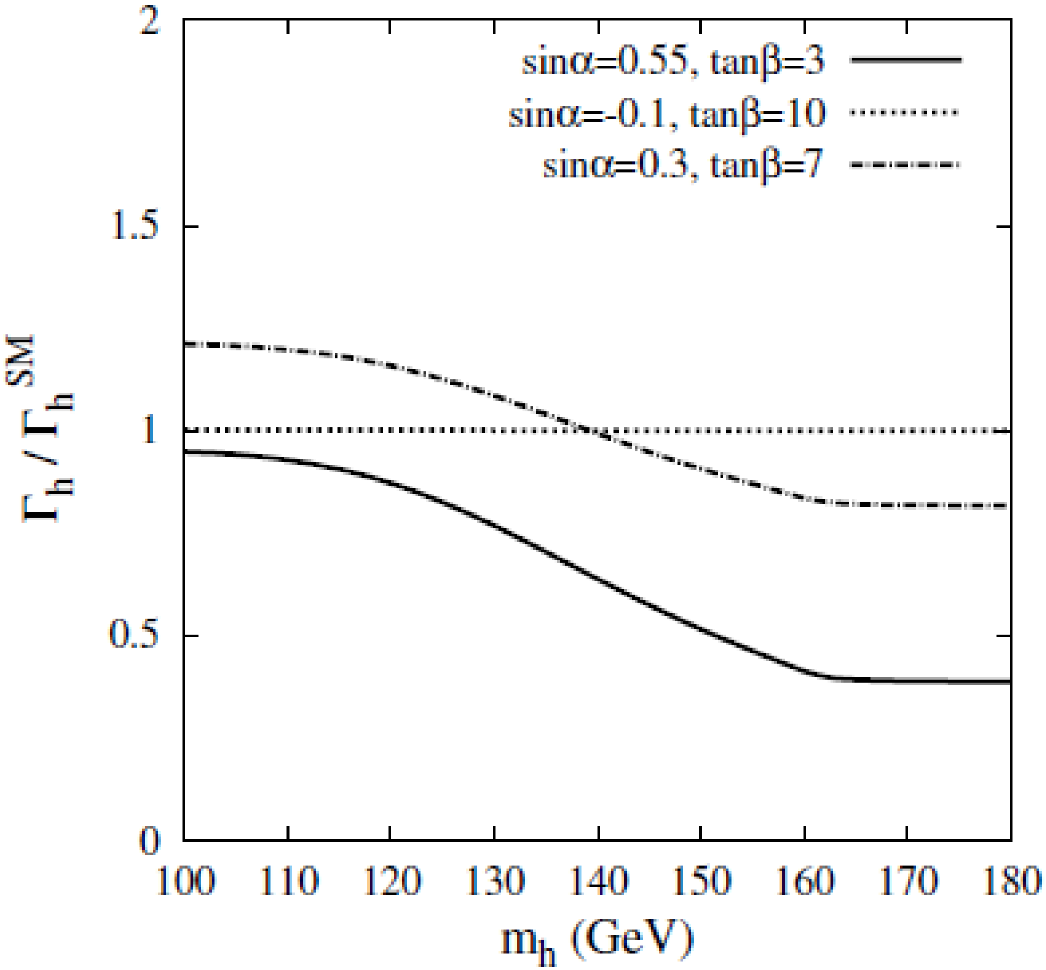


Total Width Modification

- The total width of the Higgs boson is also affected by coupling modifications.
- When $m_h \gtrsim 130$ GeV, decays to EW gauge bosons dominate and Γ_h is reduced.
- The narrow width approximation is still valid even when η-factors are substantially different from 1.



The Effect on Collider Processes

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

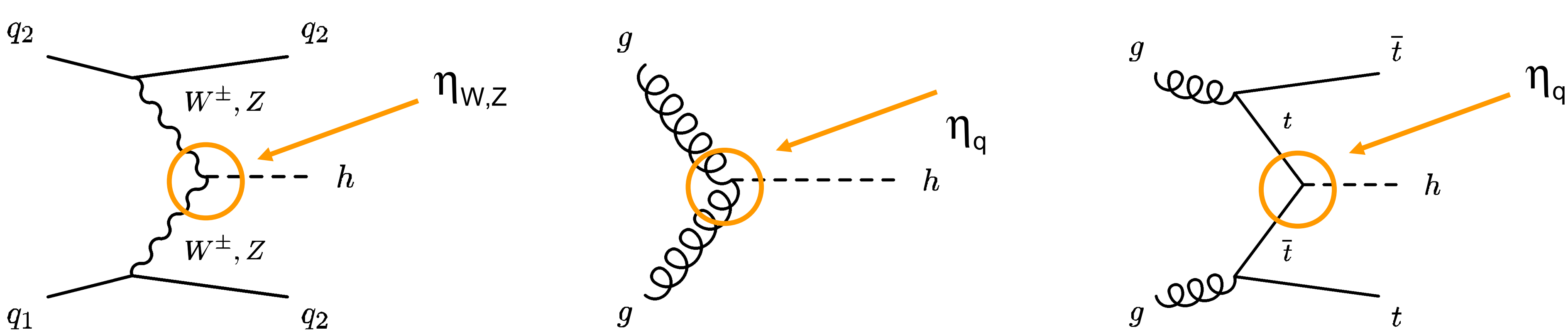
3). Modification of Total Higgs Width

$$\frac{\sigma_{(}gg \to h \to \tau\tau)}{\sigma^{SM}(gg \to h \to \tau\tau)} = \frac{\Gamma(h \to gg)}{\Gamma^{SM}(h \to gg)} \frac{\Gamma(h \to \tau\tau)}{\Gamma^{SM}(h \to \tau\tau)} \left(\frac{\Gamma_h^{tot}}{\Gamma_h^{SM,tot}} \right)^{-1}$$

1). Modification of Production Cross Section

2). Modification of Decay Widths

- All significant production mechanisms are (slightly) suppressed by η_q or $\eta_{W,Z}$.



Looking for a Leptophilia at the LHC

- Plenty of channels involving h decays directly to charged leptons are potentially useful for discovery:

Processes with $h \to \tau\tau$:

- $tth(h \to \tau\tau)$ — [Belyaev, Reina 2004] evidence at 2.7σ.
- $gg \to h \to \tau\tau$ — [Richter-Was, Szymocha 2004] preliminary only.
- $qq' \to qq'h(h \to \tau\tau)$ — Standard detection channel for light h.

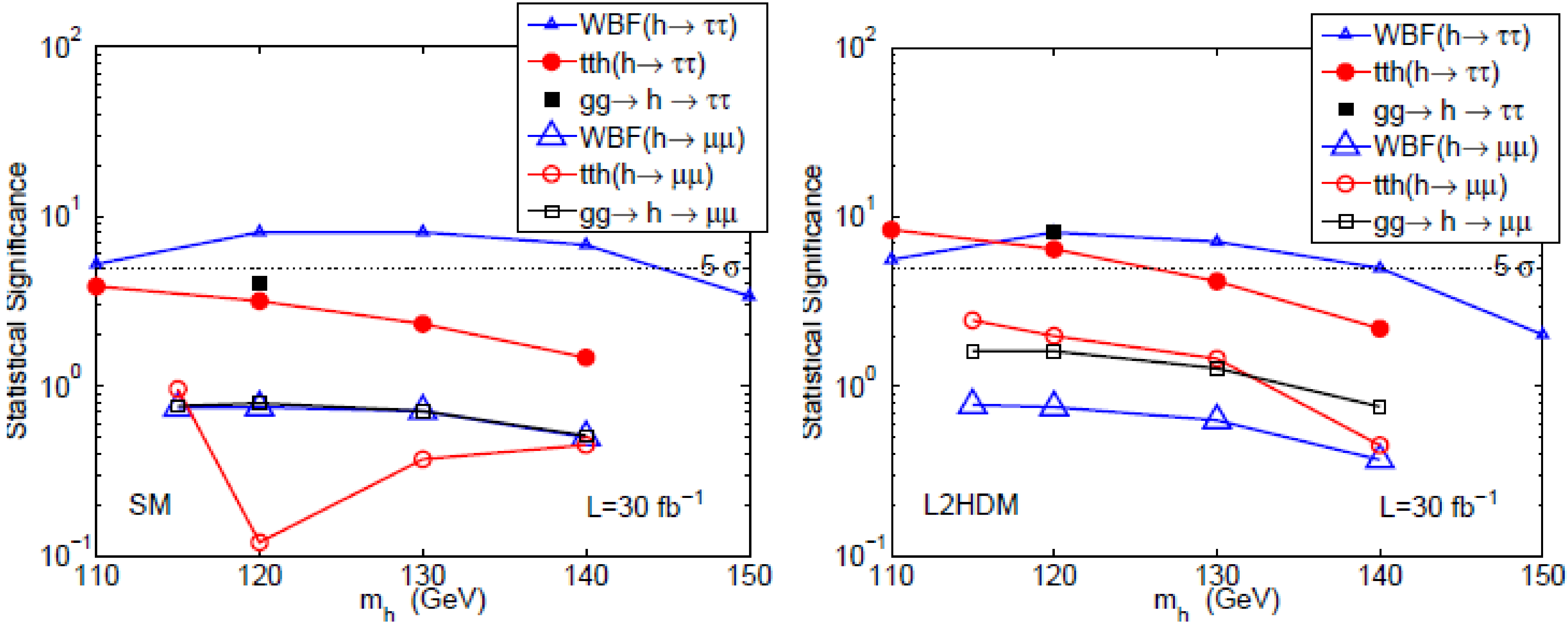
Processes with $h \to \mu\mu$:

Added Bonus: good $M_{\mu\mu}$ resolution assists in measuring couplings,in m_h, etc.

- $tth(h \to \mu\mu)$ — [Su, BT 2008] 2.6σ in SM.
- $gg \to h \to \mu\mu$ — [Han, McElrath 2002] 2.4σ in SM
- $qq' \to qq'h(h \to \mu\mu)$ — [Plehn, Rainwater 2001] 2.5σ in SM
- $Zh(h \to \mu\mu)$, $Zh(h \to \mu\mu)$ — Difficult to use.

Prospects in the Leptonic Discovery Channels

- In addition to the channels most significant for the discovery of an SM Higgs, several other, leptonic channels play a crucial role.
- Not only do $gg \to h \to \tau\tau$ and $t\bar{t}h(h \to \tau\tau)$ become important, but processes in which h decays to muons (very clean!) become significant.



The Fate of the Other Channels

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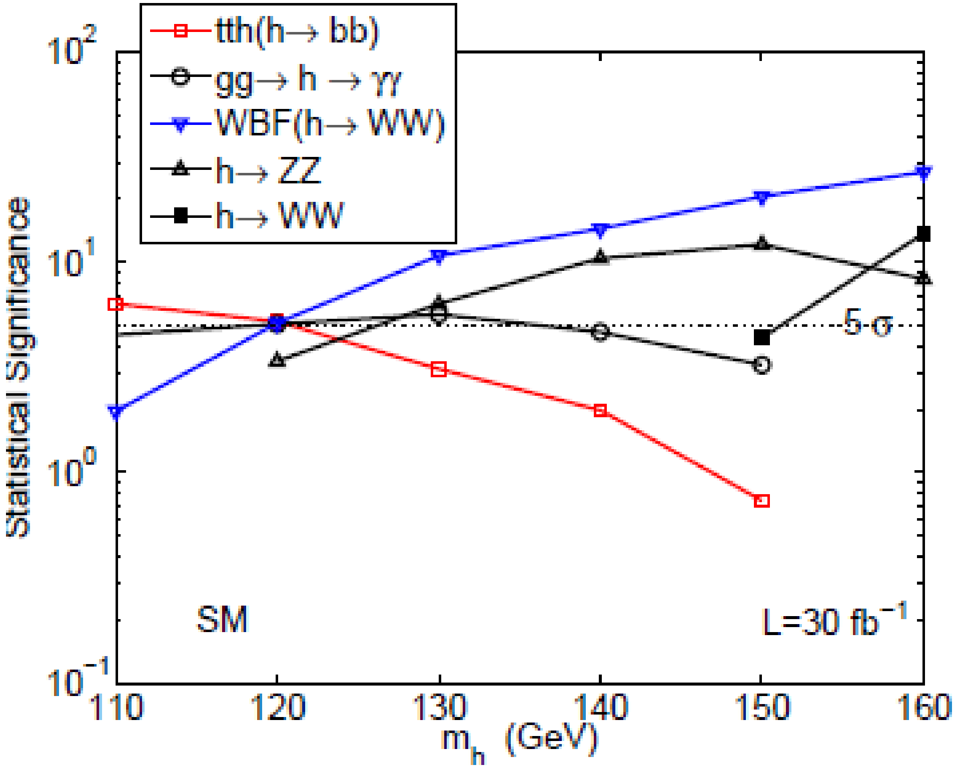
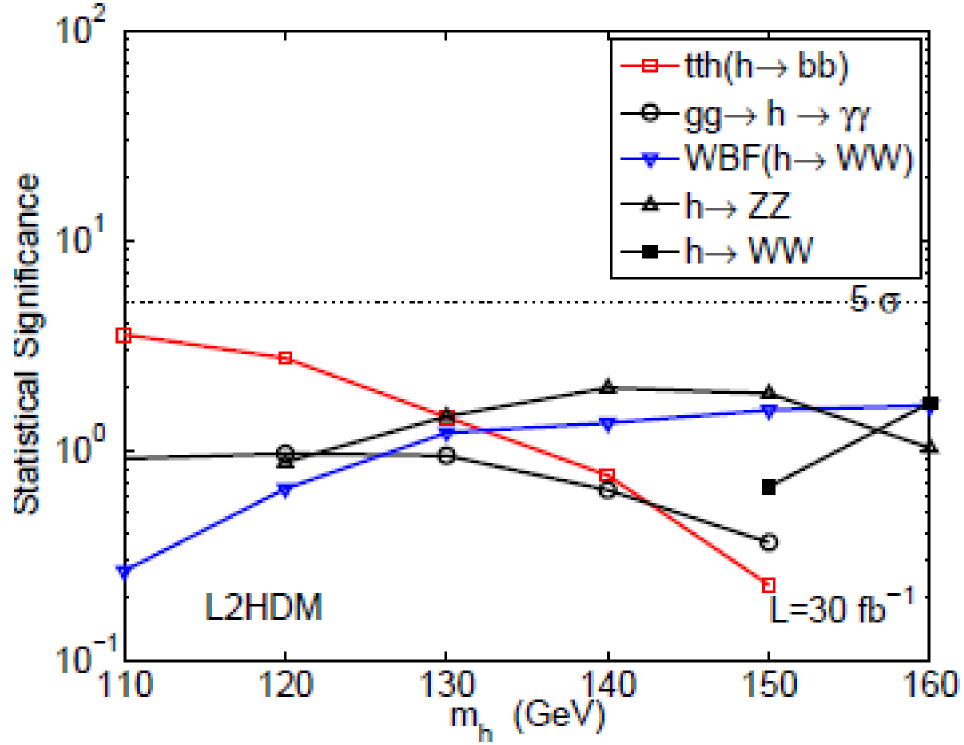
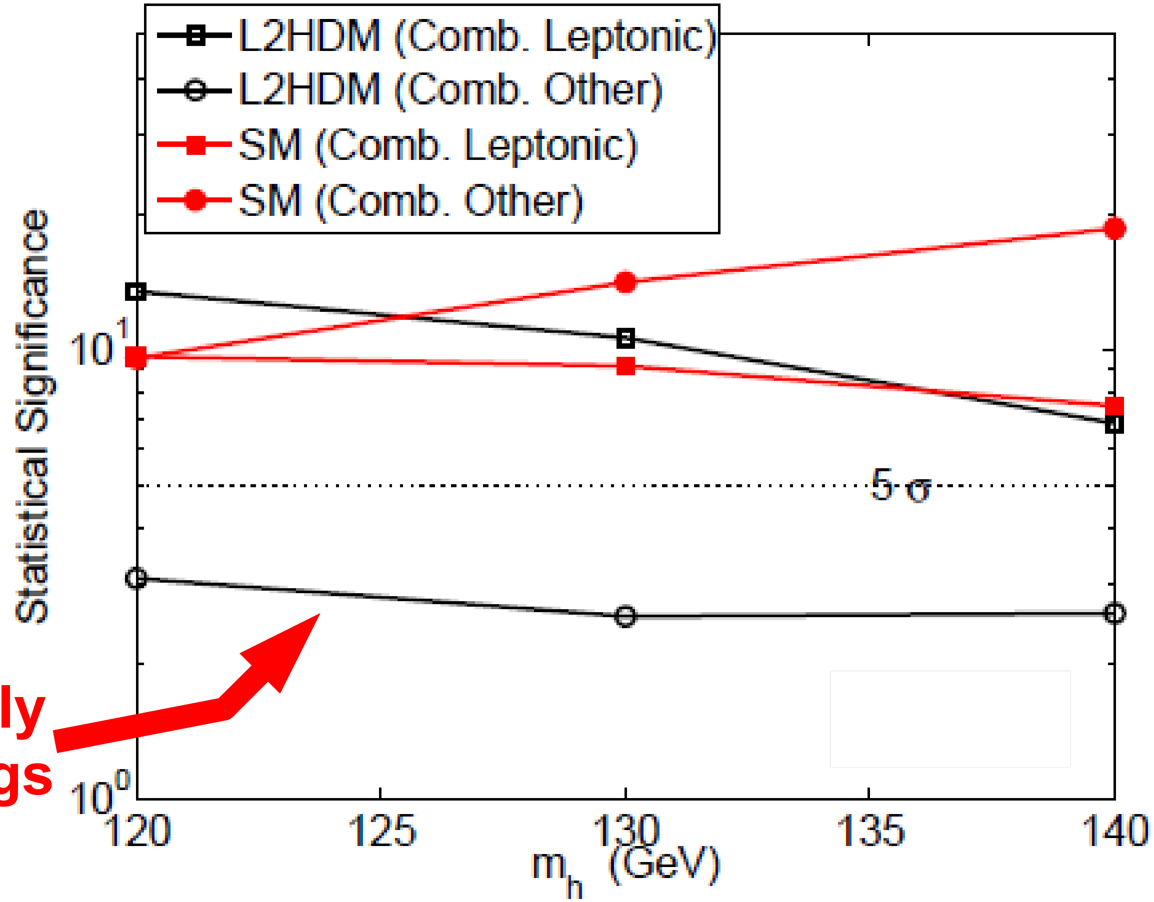




The Fate of the Other Channels, continued...

- Over large regions of parameter space, Higgs discovery is possible only via leptonic channels:

With $\mathcal{L} = 30$ fb^{-1} luminosity at both ATLAS & CMS



Not particularly useful for Higgs discovery!

Observations and Conclusions

In the near future, the relevant question will likely change from "what is the EWSB sector?" to "what does the EWSB sector tell us about the underlying theory?"

- The collider phenomenology of multiple Higgs models, and even of 2HDM is a rich one with a great deal of territory left to be explored.
- In a model where separate higgs doublets couple to quarks and leptons, the pattern of collider observables most useful for discovery is significantly different from that the one associated with an SM Higgs.
- In a leptophilic Higgs scenario, final states involving Higgs decays to leptons provide clean signatures for Higgs discovery.
- By contrast, Higgs discovery via other channels in such a model may be difficult of impossible.