Leptophilic Higgs Phenomenology at both Hadron and Muon Colliders

(And the Importance of Leptonic Decays for Higgs Discovery)

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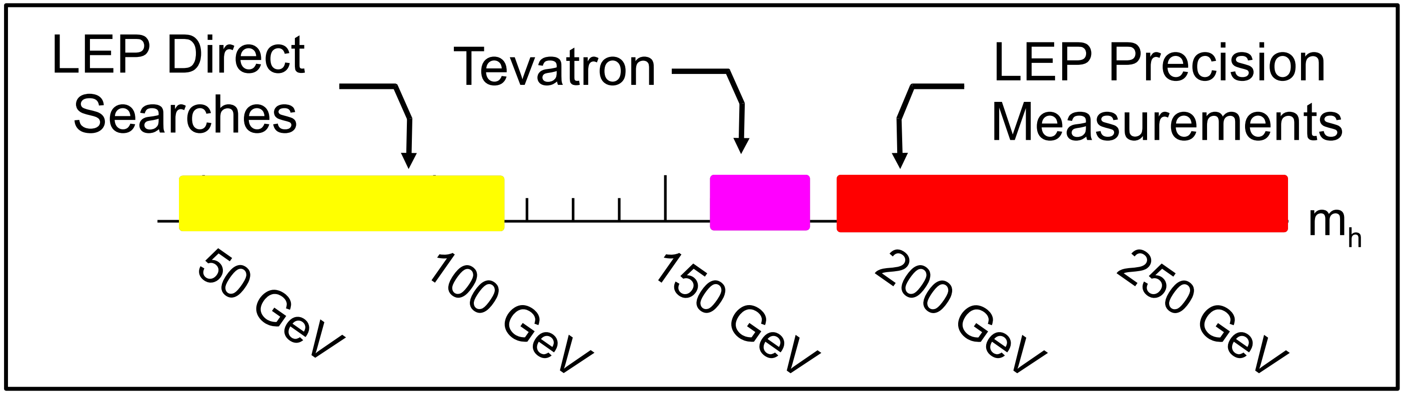
Shufang Su & BT [arXiv:0903.0667]

Searching for the Source of EWSB

- One of the primary missions of the LHC will be to search for the sector responsible for EWSB — about which we still know **very little**.
- The mass window for a SM Higgs continues to shrink (e.g. this year's new new CDF/D0 limits).
- Considerations related to naturalness and the hierarchy problem suggest that the SM should be regarded as an effective description of some high-energy theory.
- Precision data from future linear colliders will play a crucial role in characterizing the properties of that theory's EWSB sector.



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.

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]

Why look at unusual possibilities?

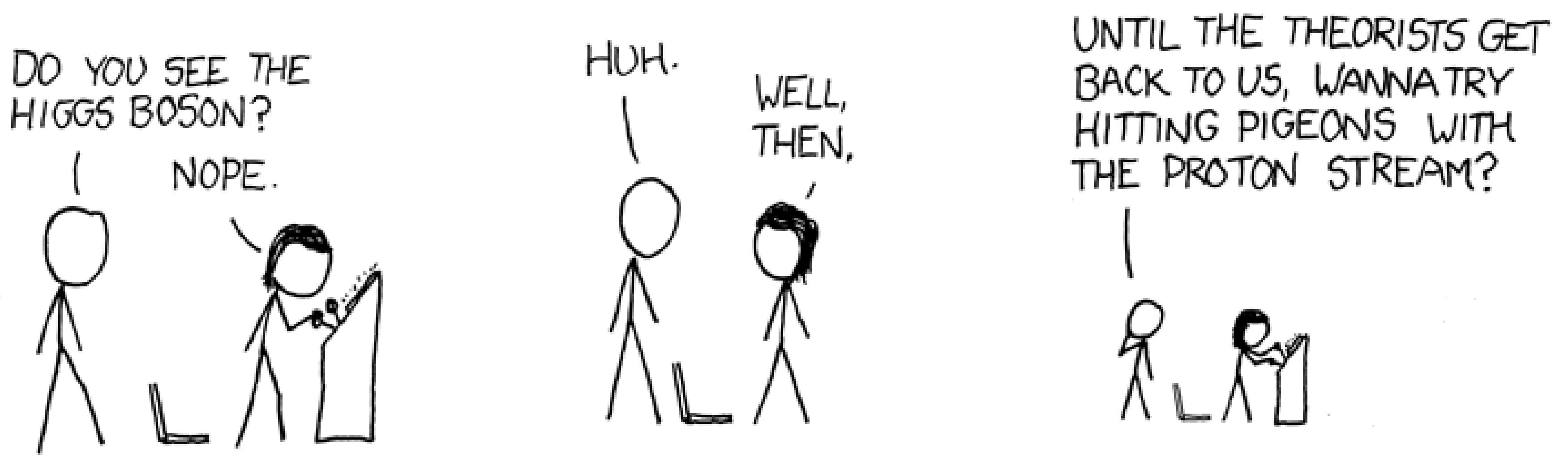
1). We don't want to "miss" a light Higgs.

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]

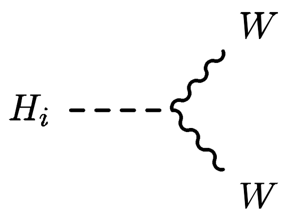


[cartoon from xkcd.com]

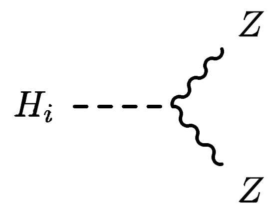
Effective Couplings from Non-Minimal Higgs Sectors

- 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].

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

Generally not universal

A Leptophilic Higgs

$\mathbb{Z}_2$ Parity Assignments:

Even: ϕ_q, q, u, d, ℓ

Odd: ϕ_ℓ, e

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

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

Higgs Potential

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

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

$\mathbb{Z}_2$ Violating

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

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.

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

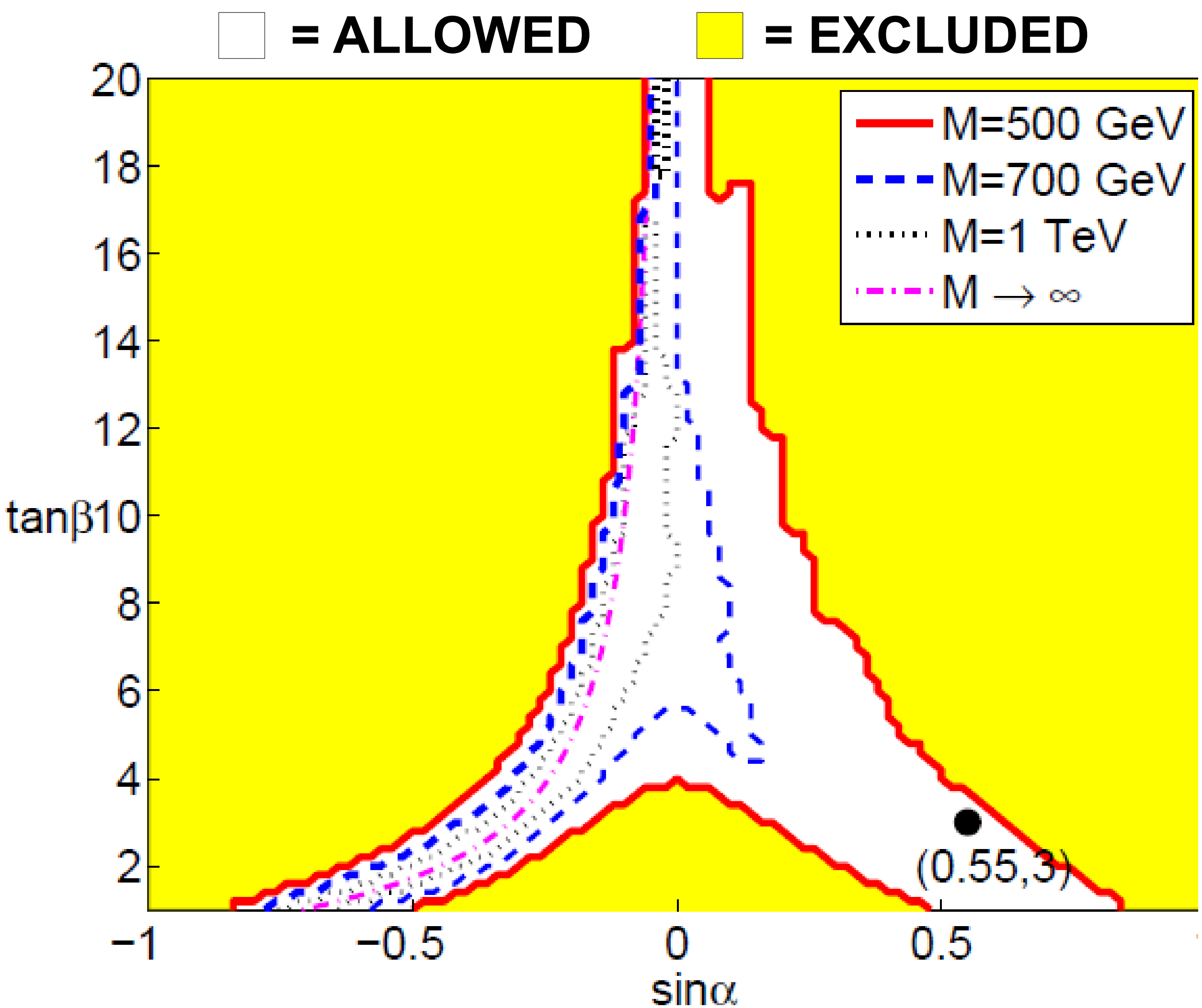
$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re}[\phi_q - v_q] \\ \mathrm{Re}[\phi_\ell - v_\ell] \end{pmatrix}$$

CP-even　CP-odd

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)

- Experimental constraints (from flavor-violation experiment, etc.) are also easily satisfied.

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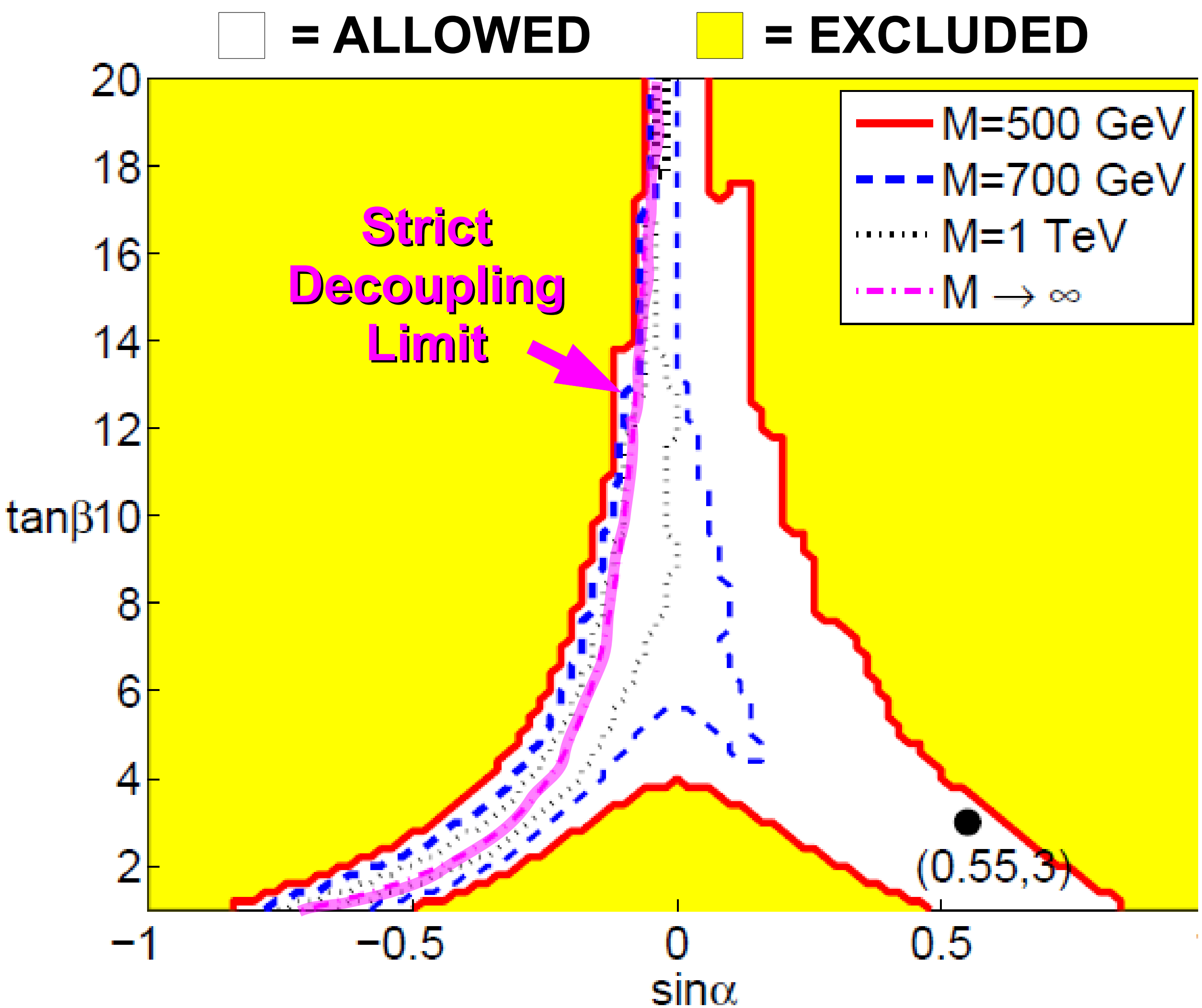

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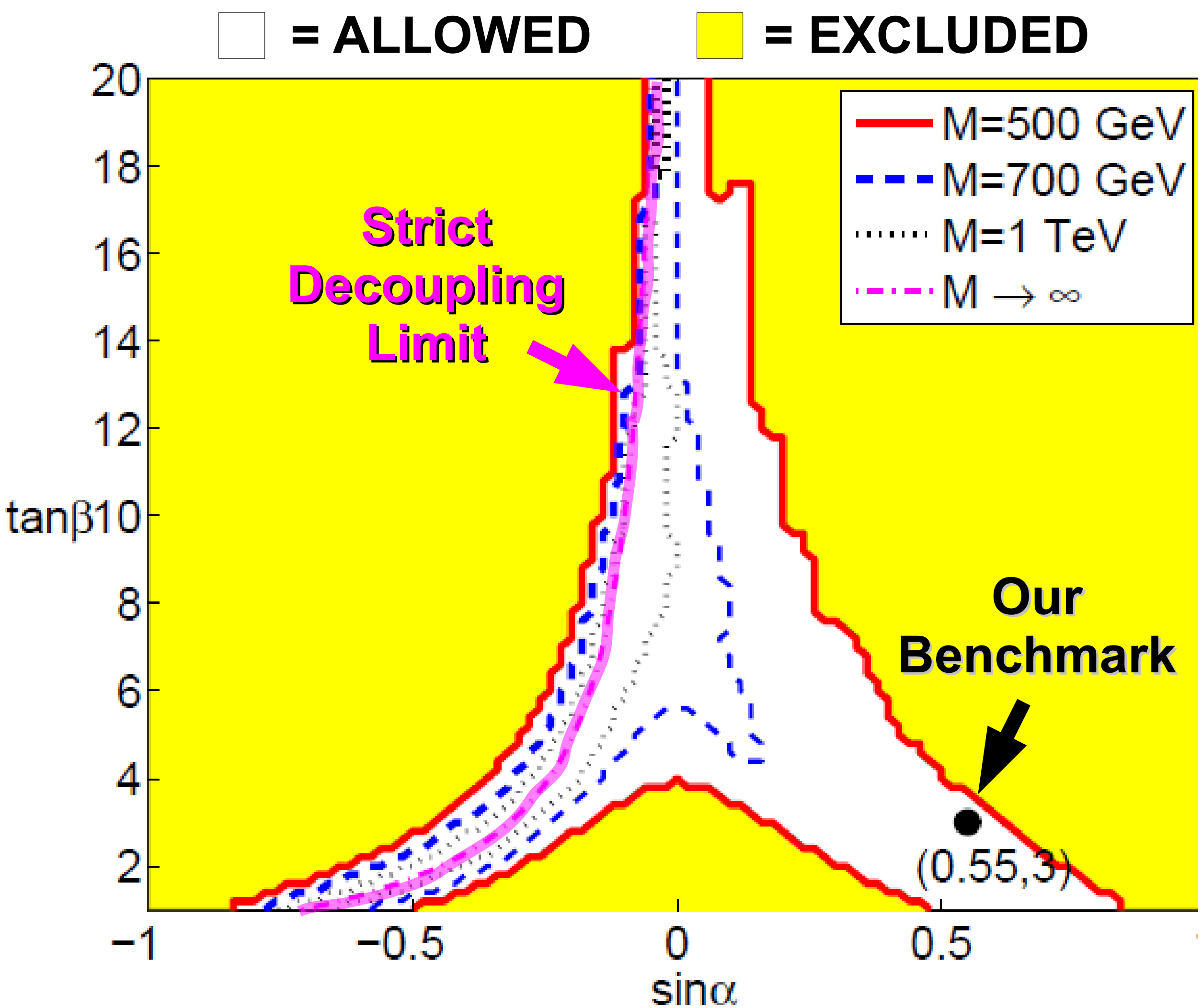

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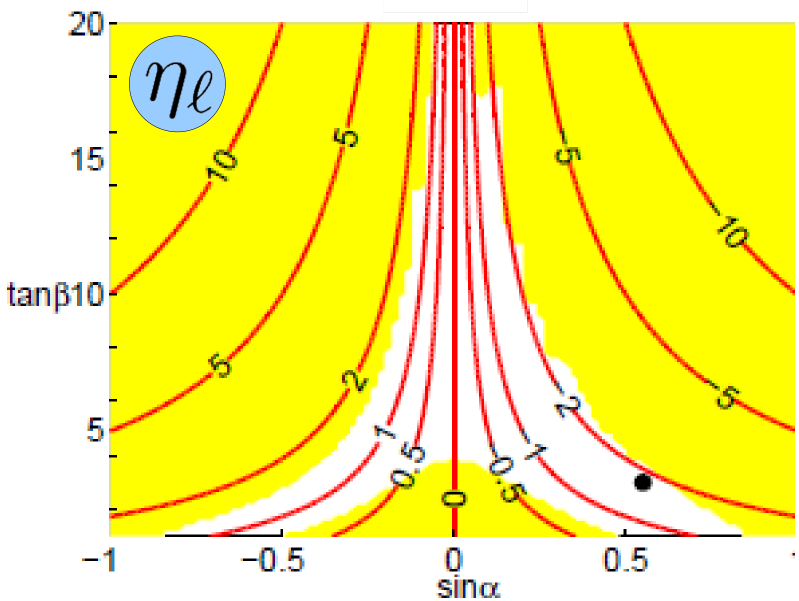
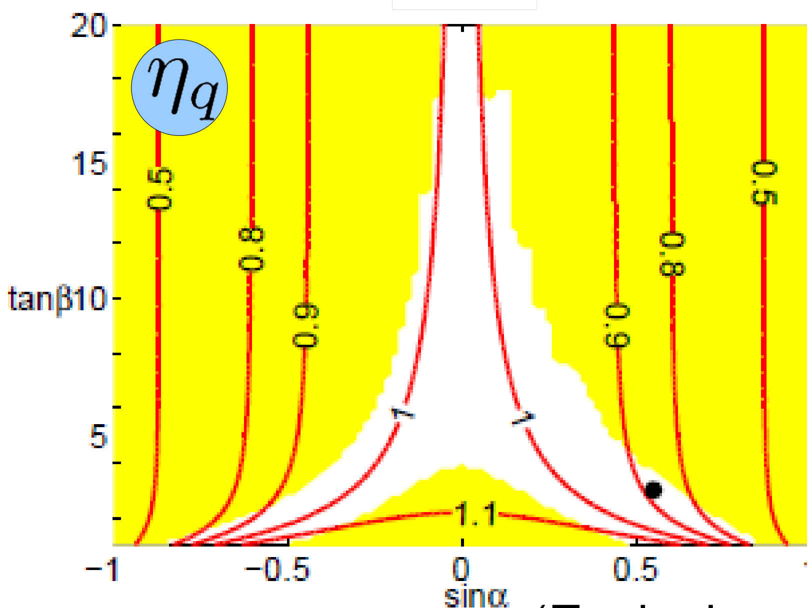
Coupling Modifications:

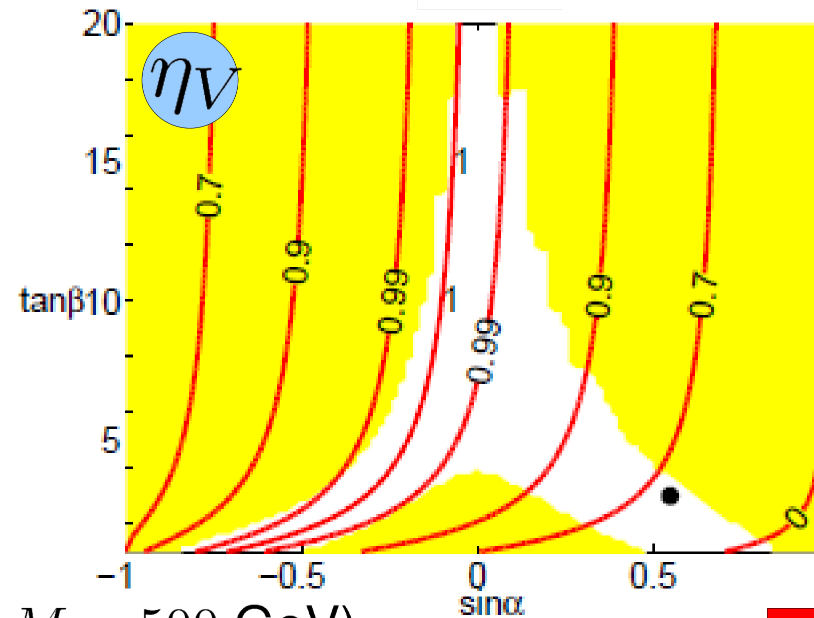


- In a 2HDM, the η parameters are determined solely by the angles α and β:

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

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





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

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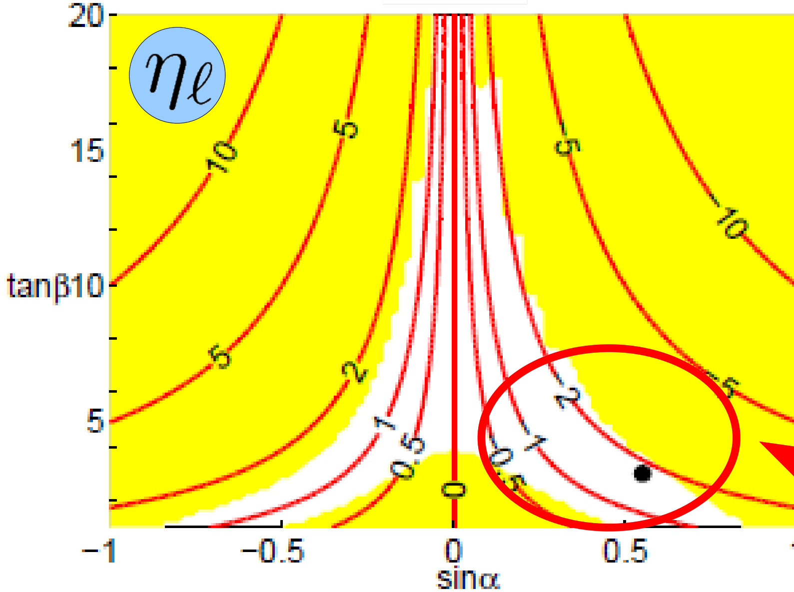

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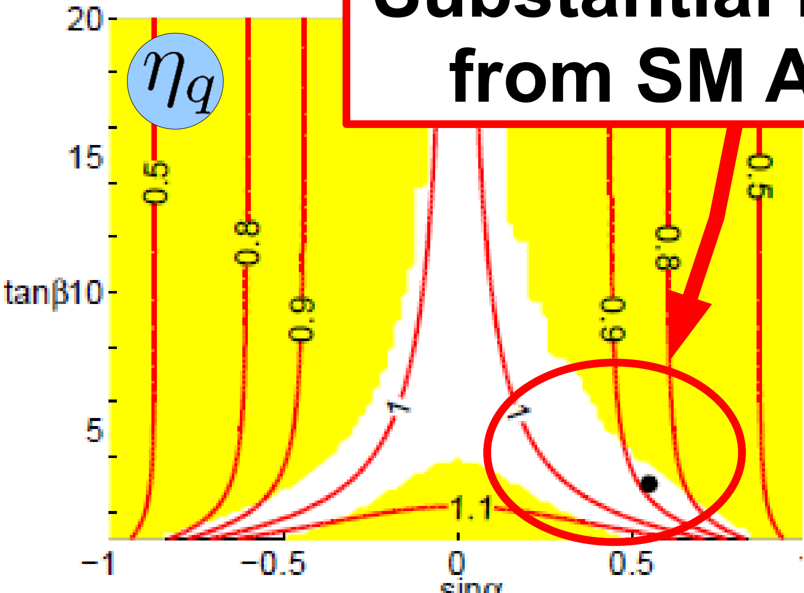
Substantial Deviations from SM Allowed!

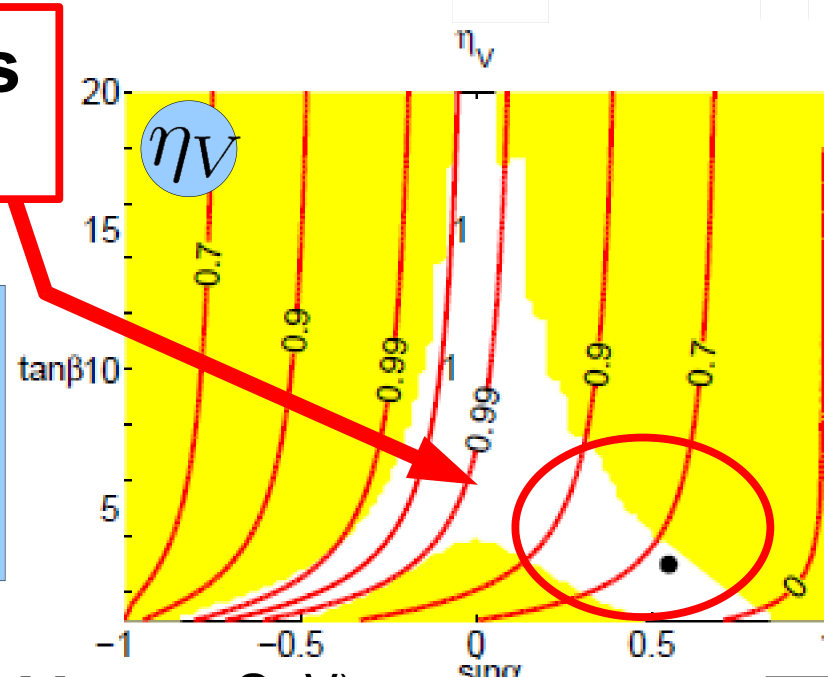


Benchmark:

$\eta_V = 0.62$

$\eta_q = 0.88$

$\eta_\ell = -1.74$



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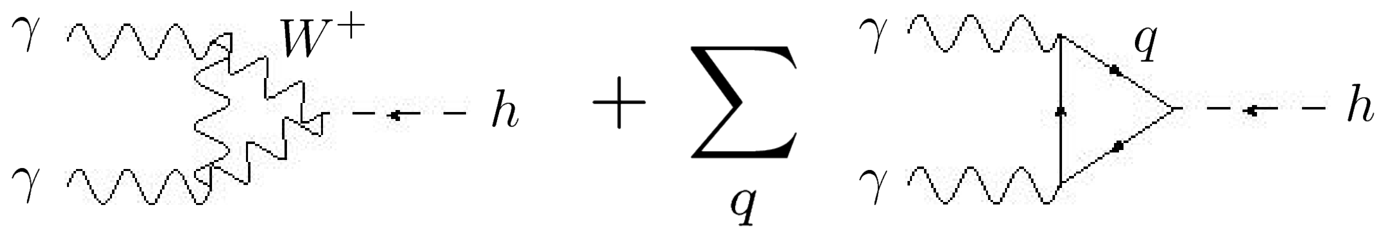
Effective Vertices:

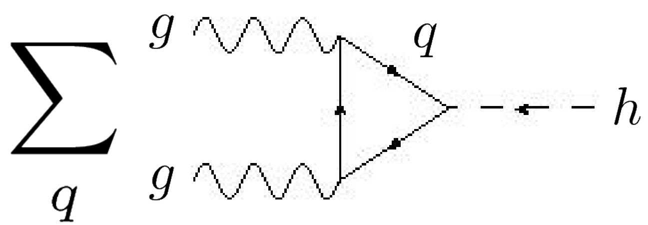
- The η-factors for certain effective couplings arising at one loop are also of interest for collider phenomenology:

1. $h\gamma\gamma$:



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

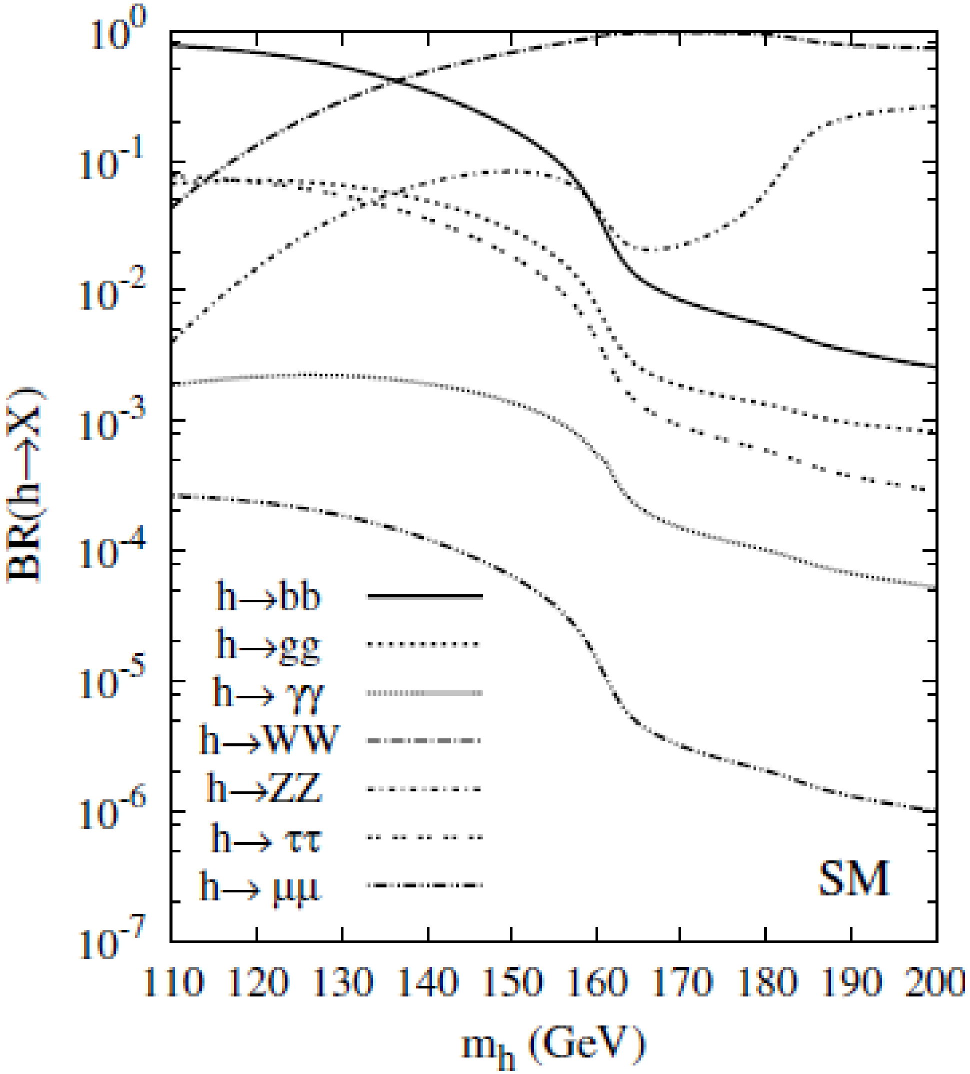
2. hgg :



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

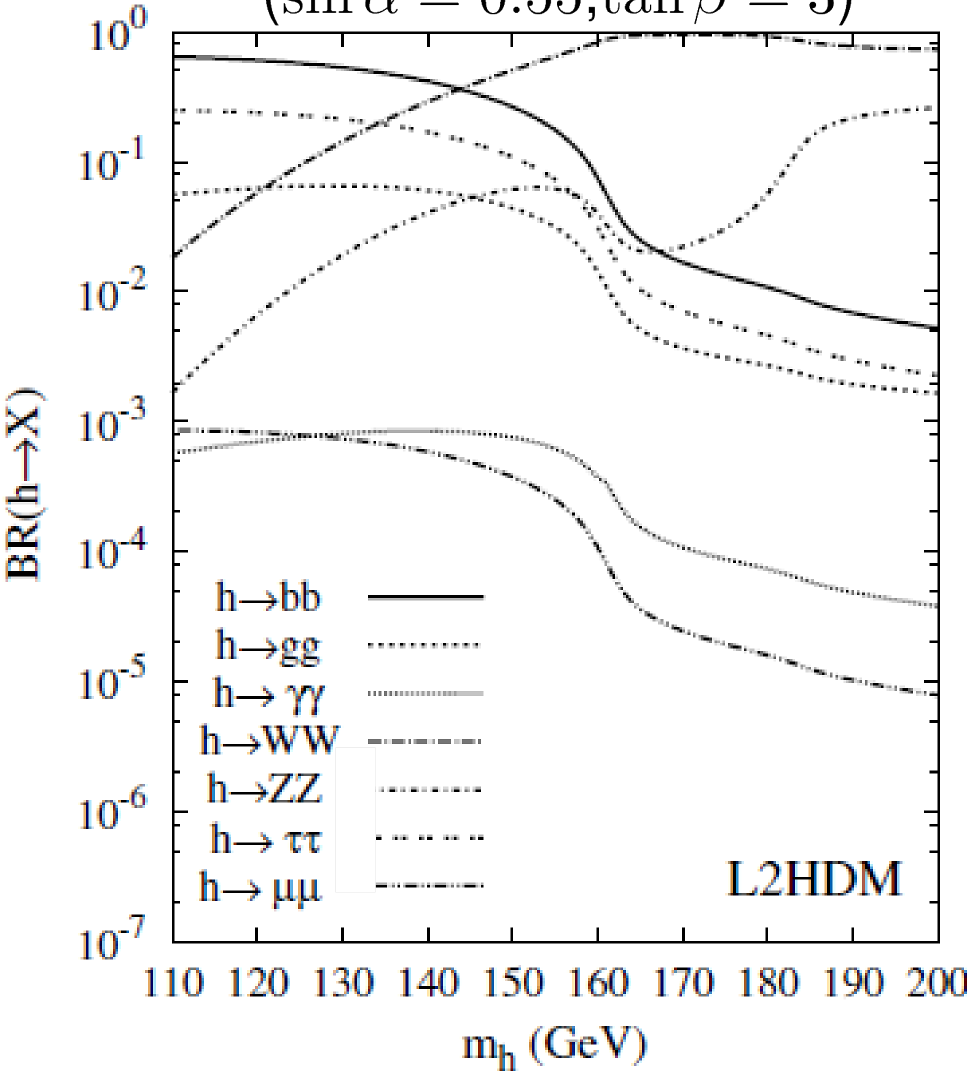
Higgs Branching Ratio Modifications

Standard Model



Leptophilic Model

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



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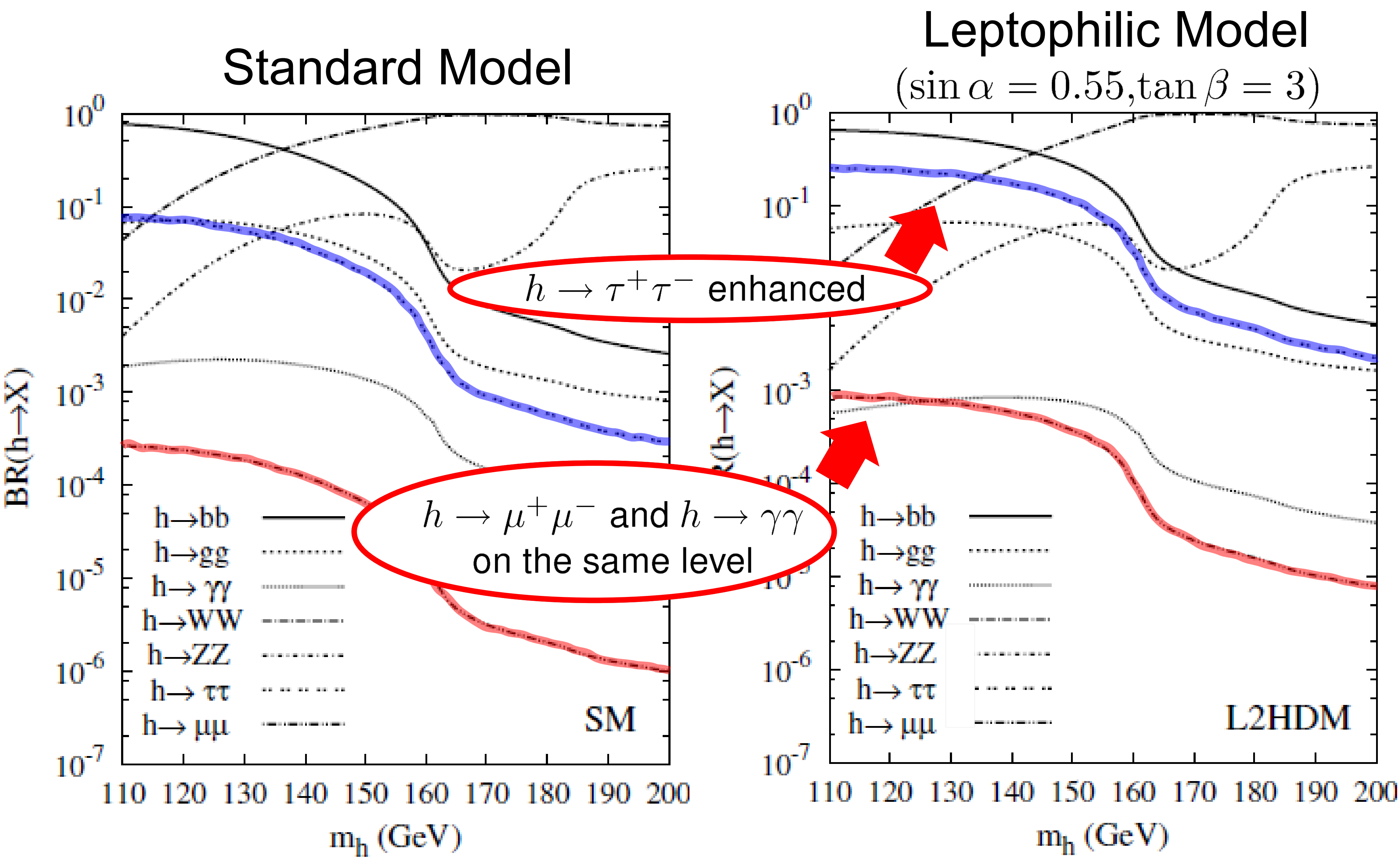
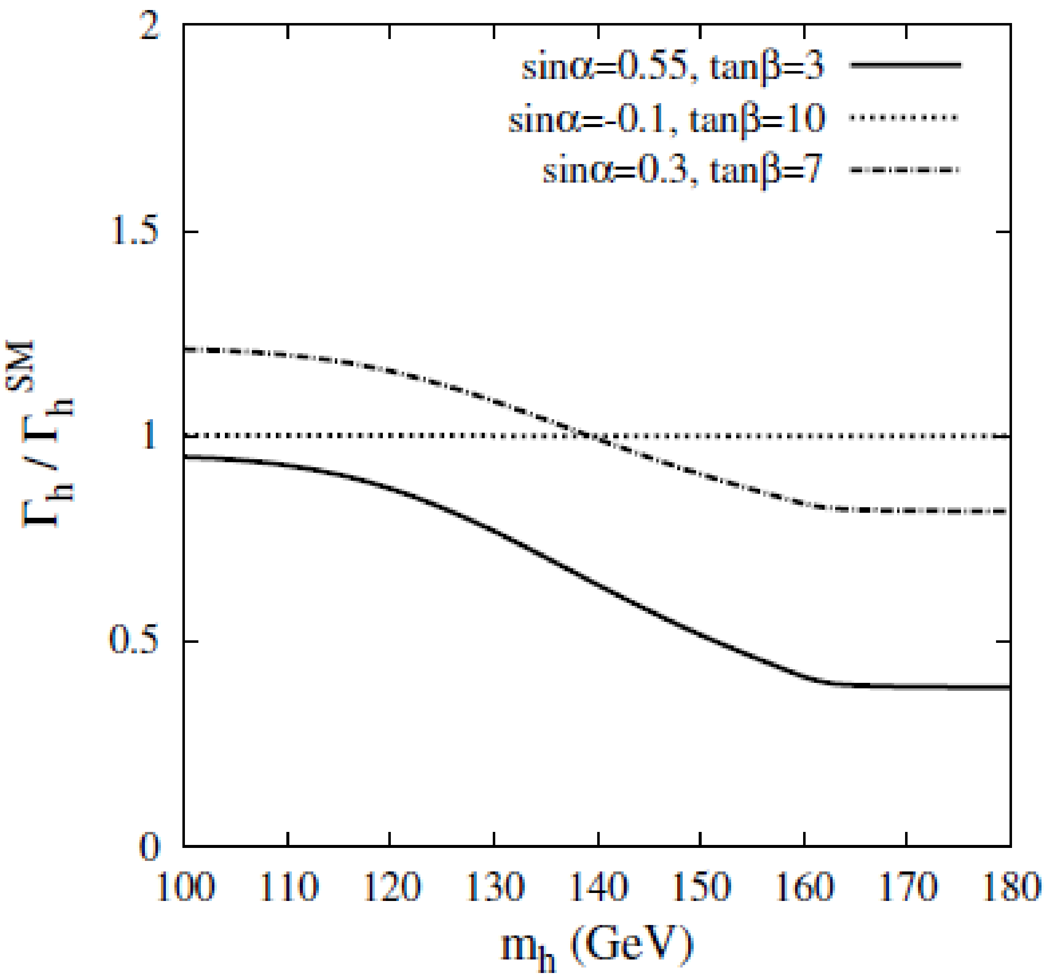


Total Width Modification

- 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.
- $\sigma(XX \to h) \propto \Gamma(h \to YY)$ at leading order.

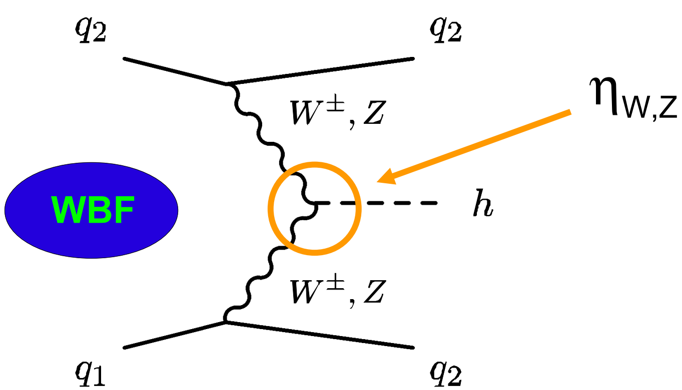
3). **Modification of Total Higgs Width**

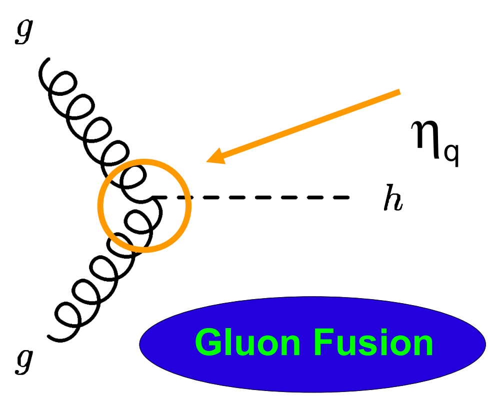
$$\frac{\sigma_{(}XX \to h \to YY)}{\sigma^{SM}(gg \to h \to \tau\tau)} = \frac{\Gamma(h \to XX)}{\Gamma^{SM}(h \to XX)} \frac{\Gamma(h \to YY)}{\Gamma^{SM}(h \to YY)} \left(\frac{\Gamma_h^{tot}}{\Gamma_h^{SM,tot}} \right)^{-1}$$

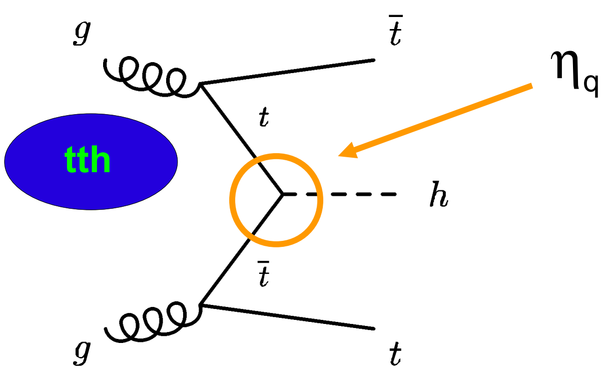
1). **Modification of Production Cross Section**

2). **Modification of Decay Widths**

- At LHC, all significant production channels are **suppressed** (slightly) by η_q or $\eta_{W,Z}$.



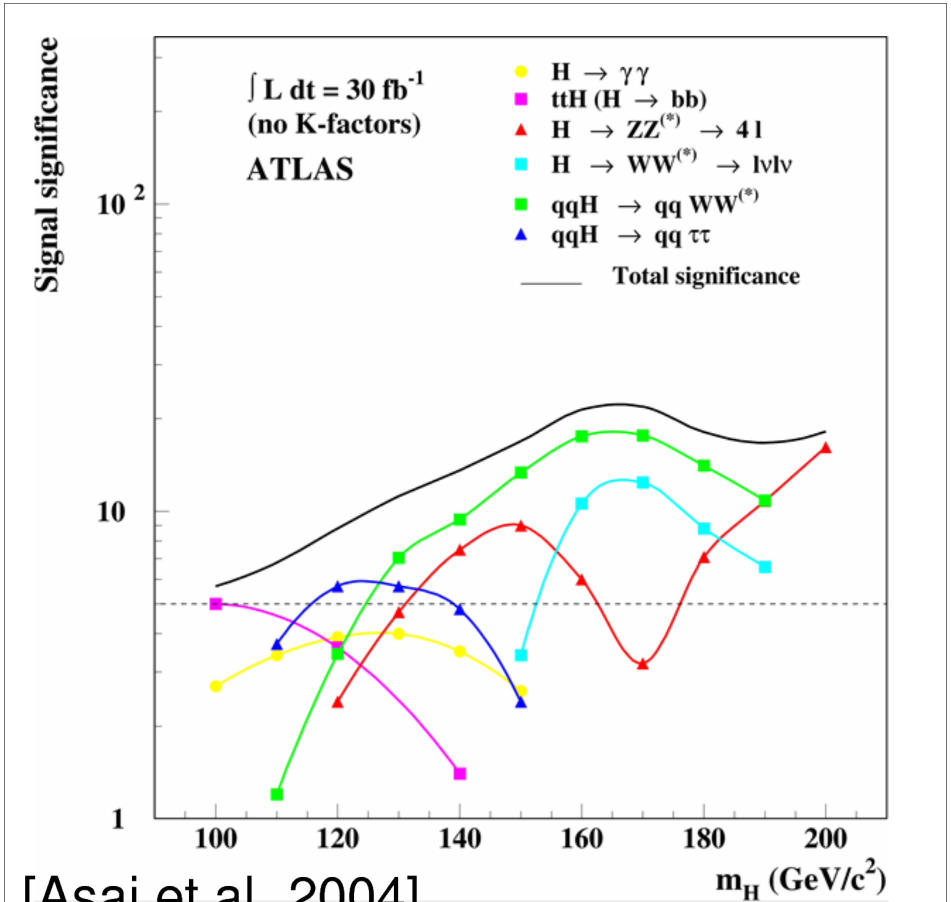




LHC: The Standard Channels

- For a light Standard-Model Higgs (115 GeV $\lesssim m_h \lesssim 140$ GeV), the particularly promising discovery channels are . . .

- **Gluon-fusion processes**:
  $gg \to h \to \gamma\gamma$.
- **Weak boson fusion processes**:
  $h \to WW^{(*)}, ZZ^{(*)}, \tau\tau$.
- tth **processes**:
  none terribly important in the experimentally-allowed m_h range.



[Asai et al. 2004]

Leptonic Higgs-Discovery Channels

- 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.

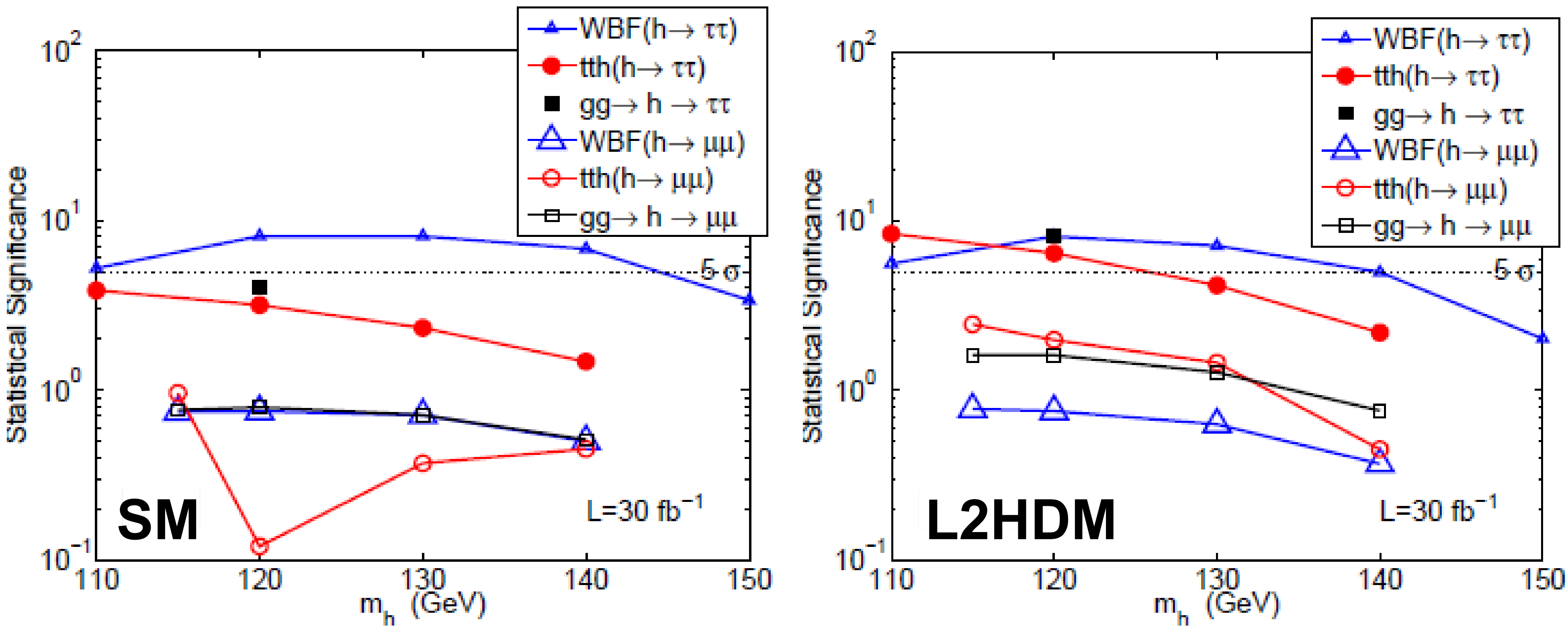
Processes with $h \to \mu\mu$:

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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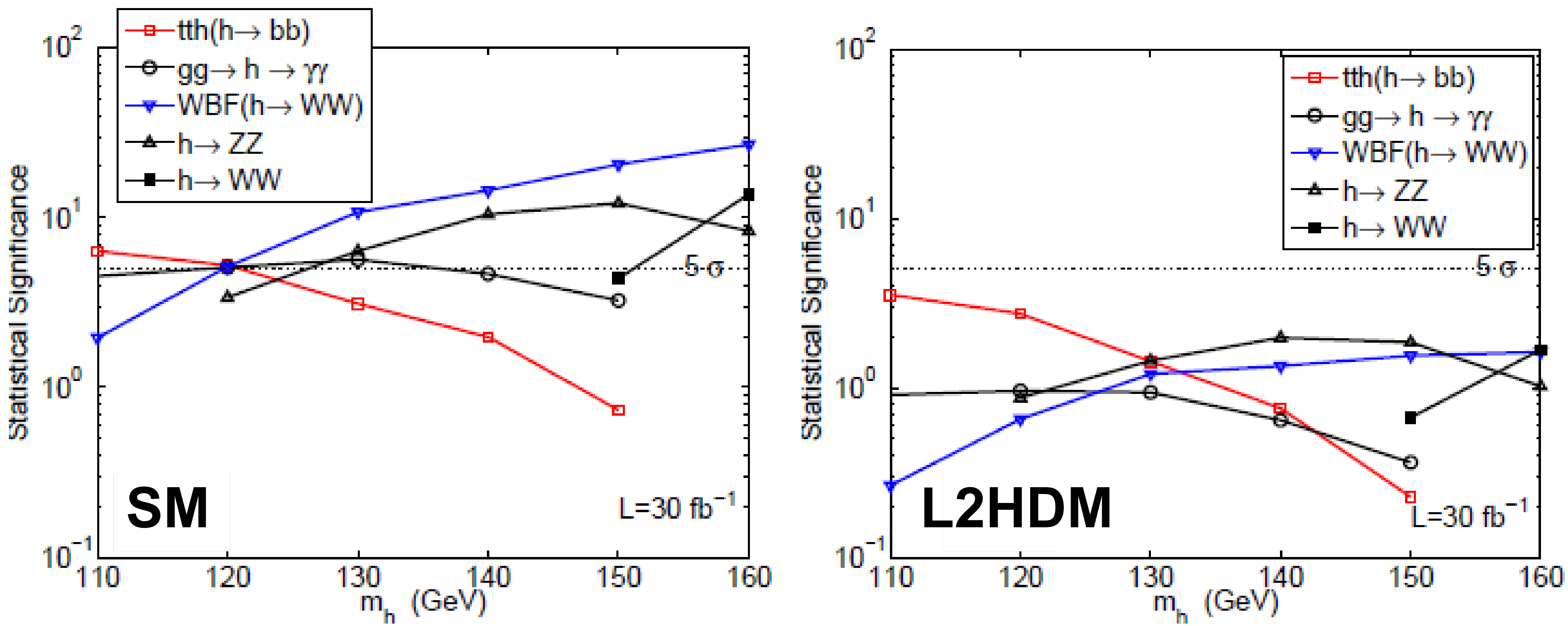
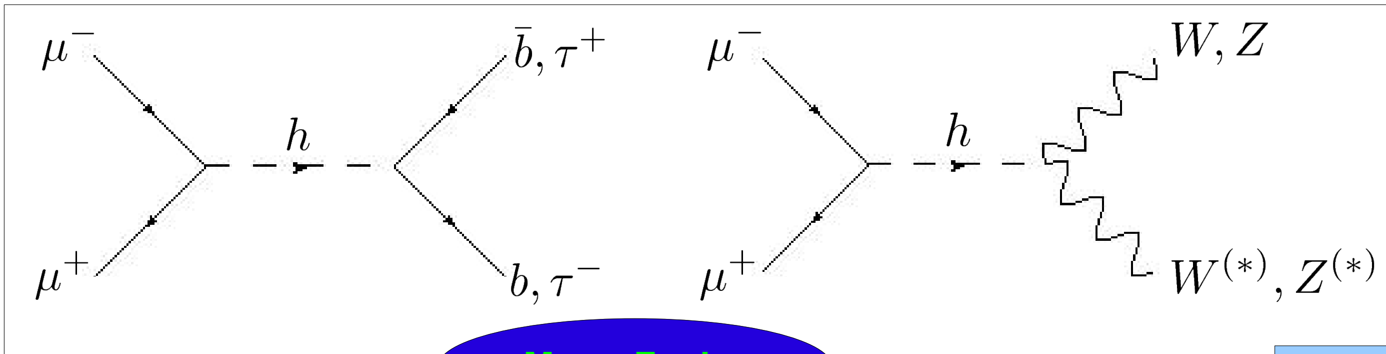
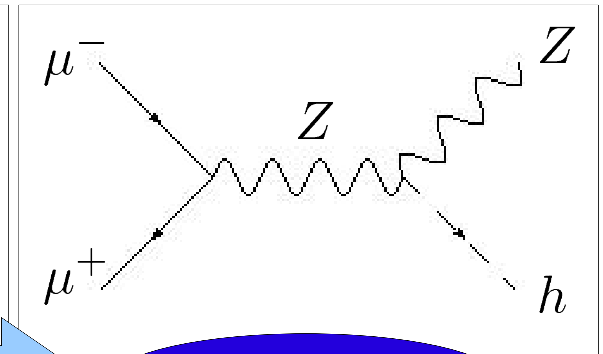


Higgs Detection at Muon Colliders

- Both s-channel Higgs production and ZZh associated production channels can be important.

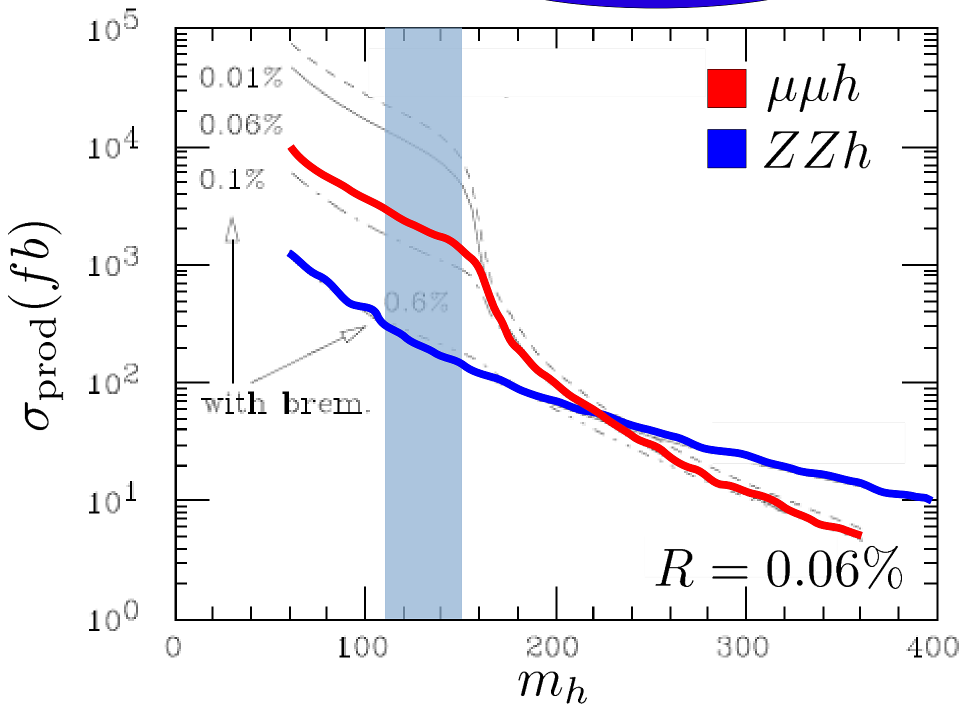


Muon Fusion



ZZh Production

Offers the best discovery prospects for a light Higgs [Barger et al. 1996].

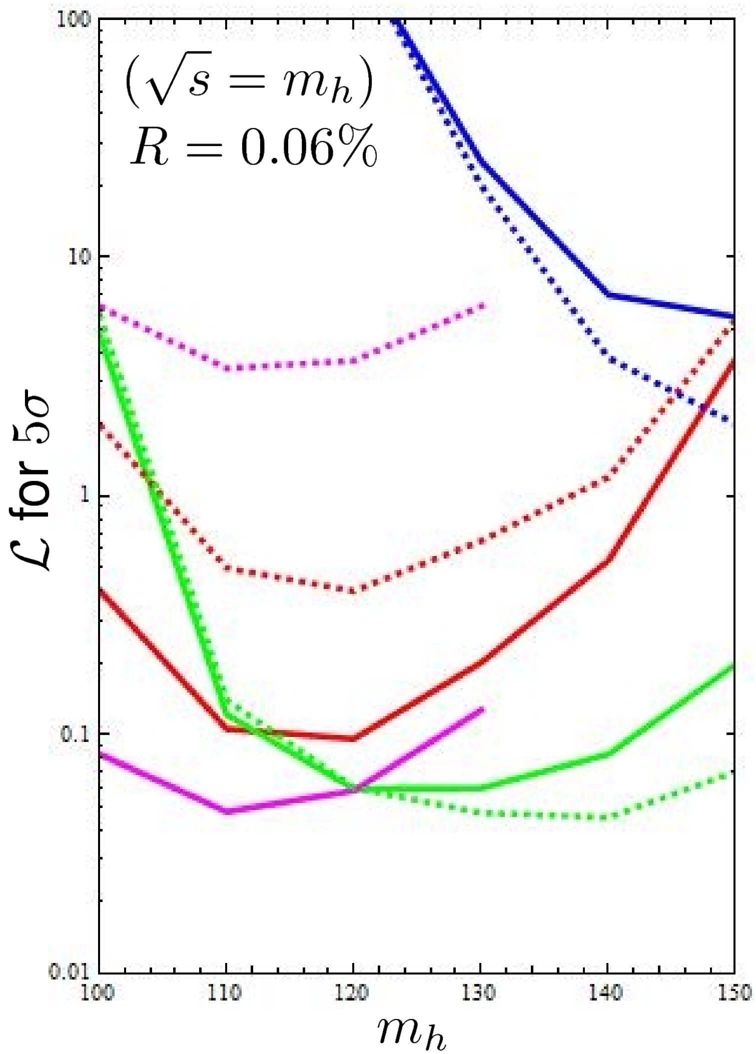


- The most promising discovery channels involve h decays to $\tau^+\tau^+$, $b\bar{b}$, $WW^{(*)}$, and $ZZ^{(*)}$.

Once h is discovered, s-channel processes will play a crucial role in measuring m_h, couplings.

Higgs Detection at Muon Colliders

- For our benchmark scenario, s-channel Higgs-production processes benefit from a substantial $\eta_{h\mu\mu}$ enhancement factor.



- Consider "Higgs-hunting" by scanning at low energies: $\sqrt{s} \sim 100$ - 160 GeV.
- Substantial deviation in $\mu\mu \to h \to \tau\tau$ discovery potential relative to the SM.
- Results for other processes remain similar, due to production cross-section enhancement.

$\mu\mu \to h \to \tau\tau$
$\mu\mu \to h \to bb$
$\mu\mu \to h \to WW$
$\mu\mu \to h \to ZZ$
Dotted: SM
Solid: L2HDM

Leptonic signatures can be of crucial importance at muon colliders as well.

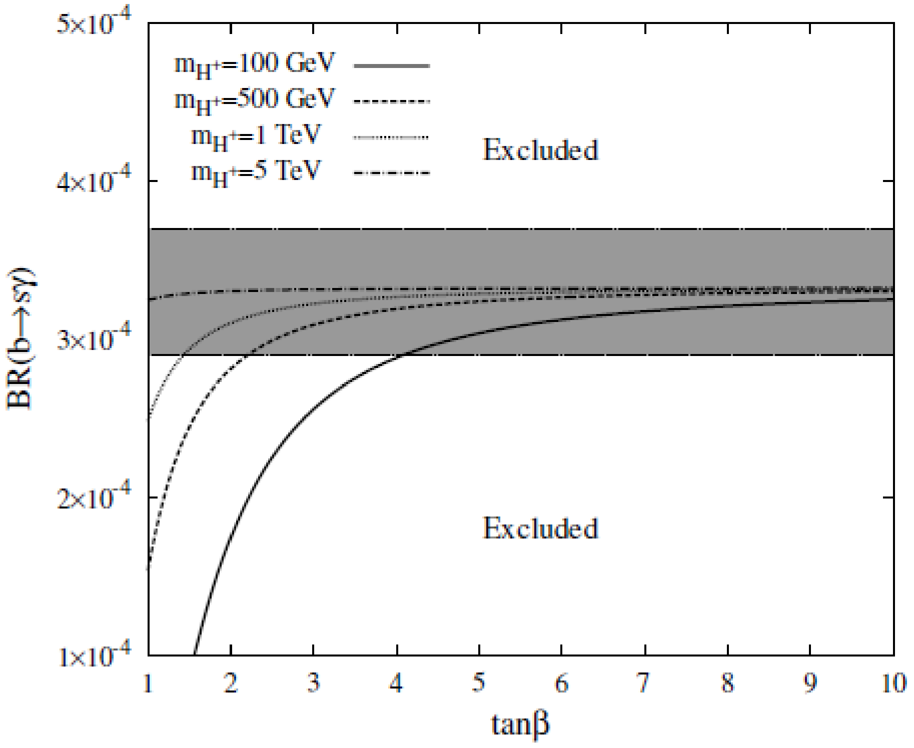
Observations and Conclusions

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?"

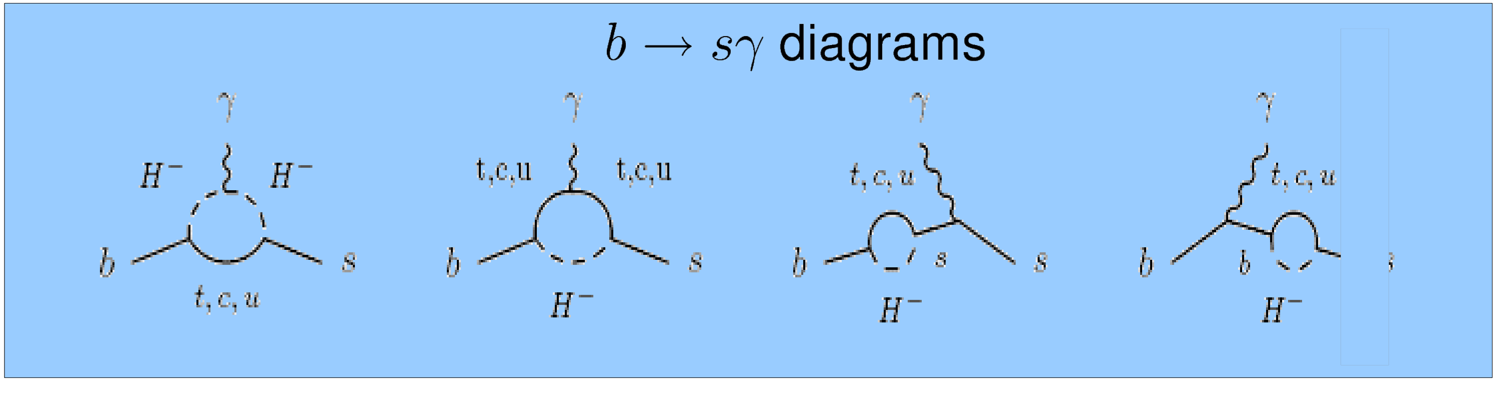
- The collider phenomenology of multiple Higgs models, and even of 2HDM is a rich one with a great deal of territory left to be explored.
- In a model where separate higgs doublets couple to quarks and leptons, the pattern of collider observables most useful for discovery is differs significantly from that most useful for discovering a SM Higgs.
- In a leptophilic Higgs scenario, final states involving Higgs decays to leptons provide (perhaps the only) clean signatures for Higgs discovery at LHC.
- Significant modifications in muon-collider phenomenology as well.

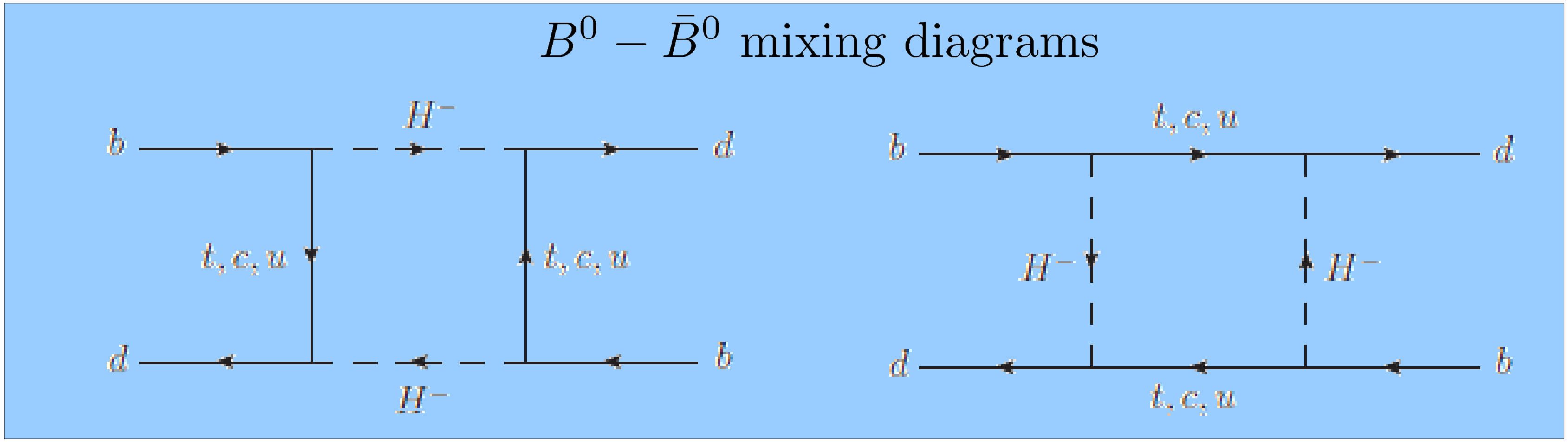
Extra Slides

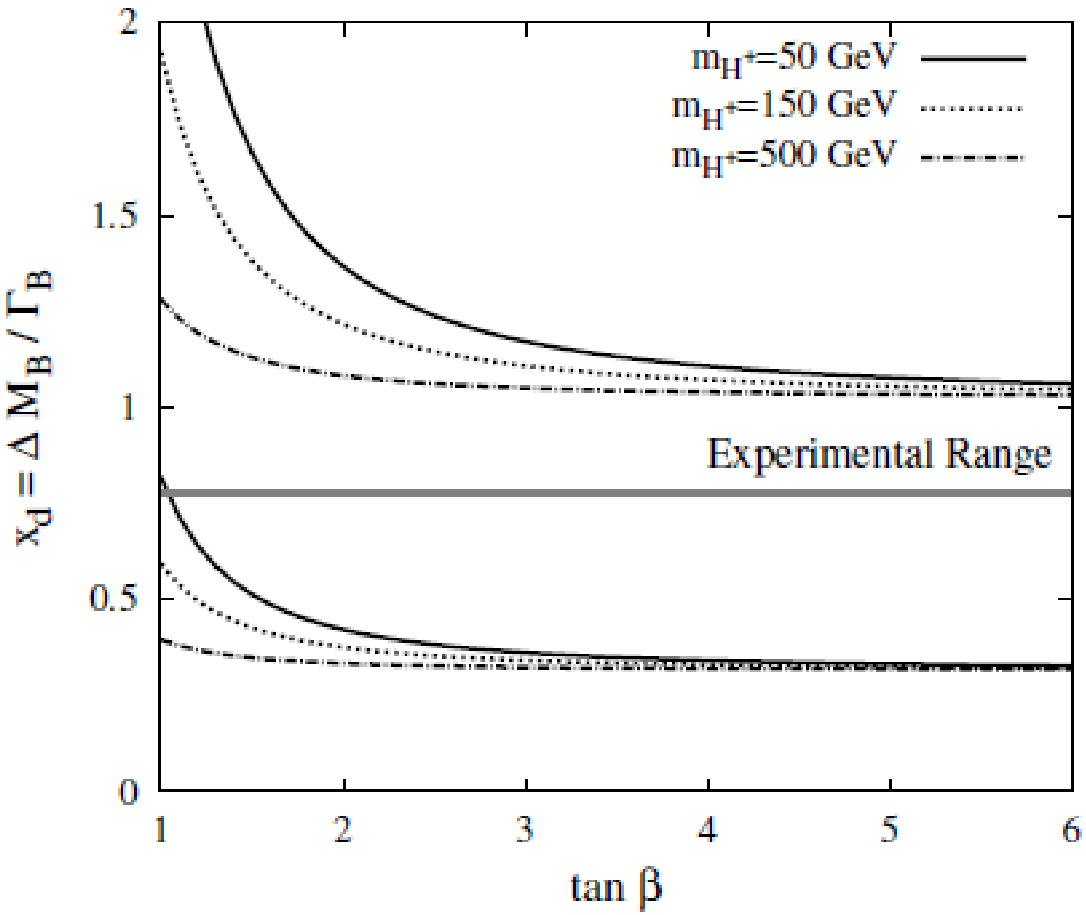
Flavor Violation Constraints



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

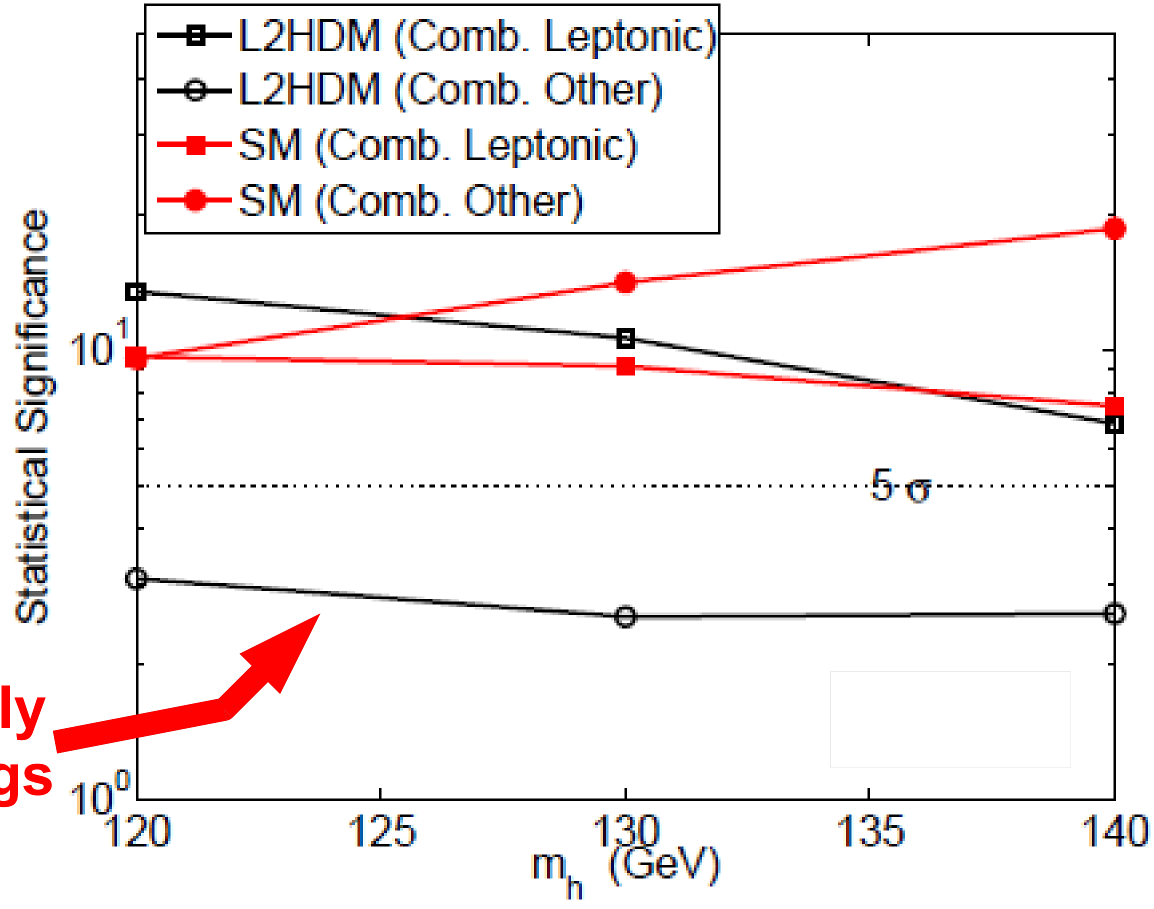
Large Theoretical Error Bars (bag factor, etc.)

Verdict: Experimental constraints ALSO satisfied.

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!