Phenomenology of a Lepton-Specific Higgs

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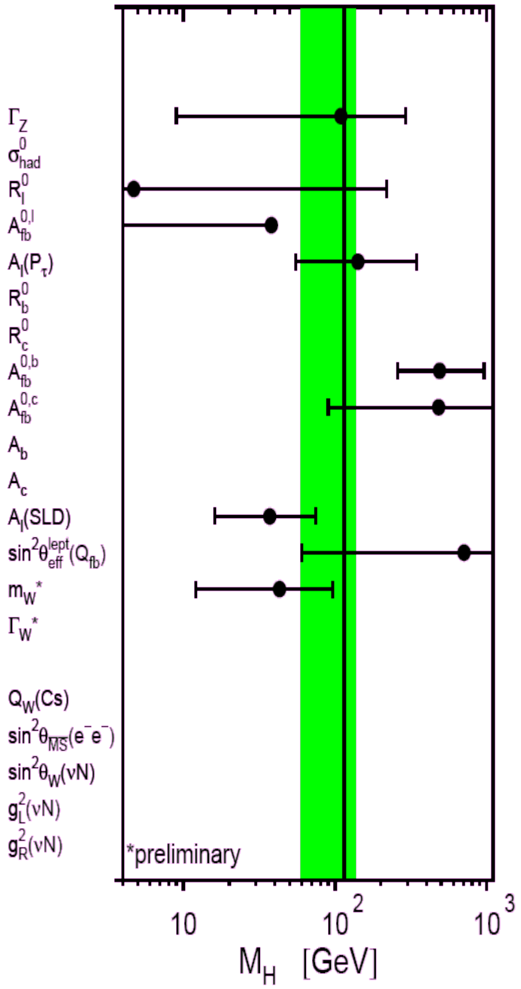
Shufang Su & Brooks Thomas, in Preparation

What do we know about EWSB?

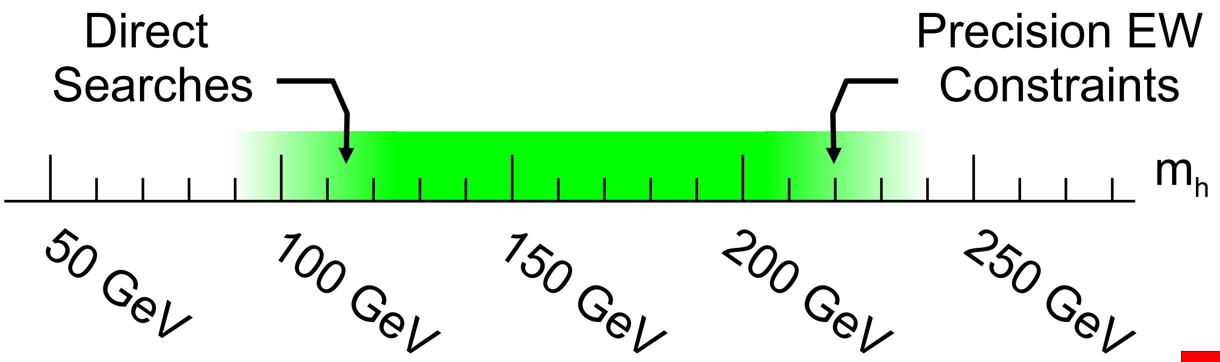
- Not Much. We don’t yet know how EWSB works or how many effects contribute.



- 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.



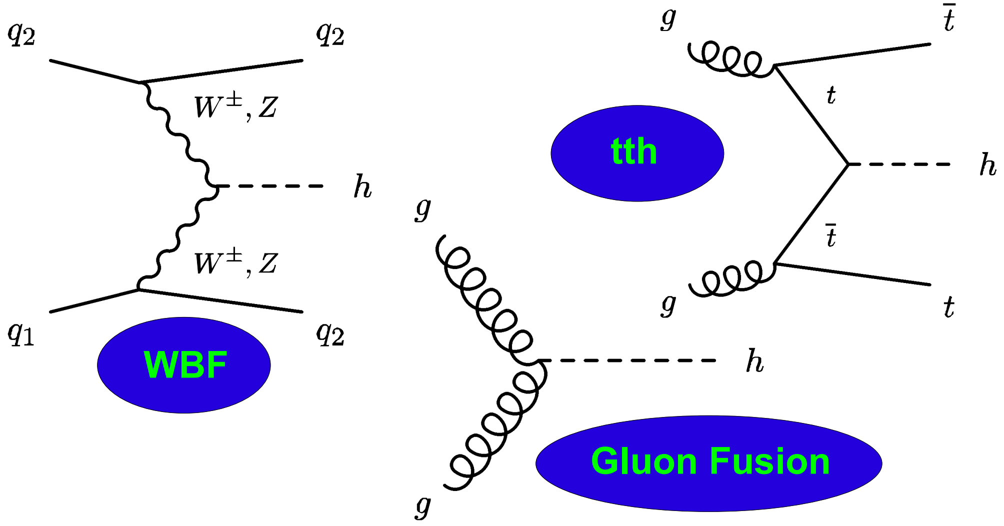
Detecting a SM Higgs at the LHC

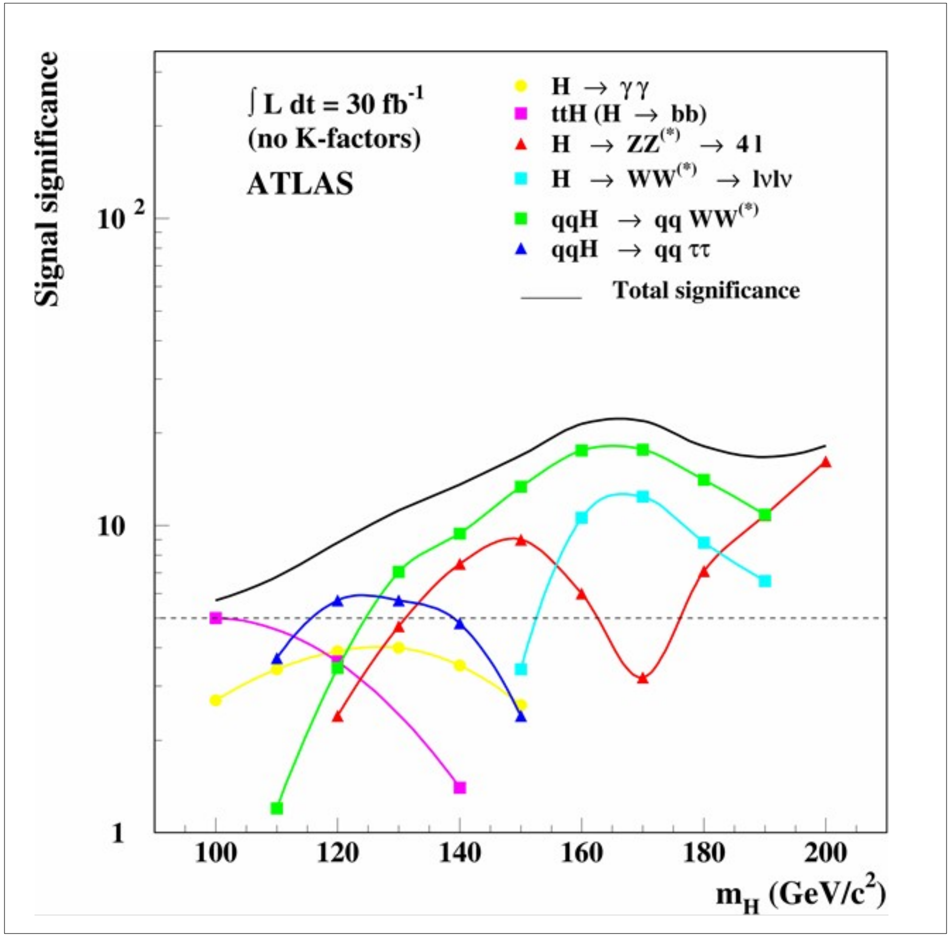
- For a light Higgs (115 GeV $\lesssim m_h \lesssim 150$ GeV), there are three discovery channels that are particularly promising.

- $gg \to h \to \gamma\gamma$ 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.





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

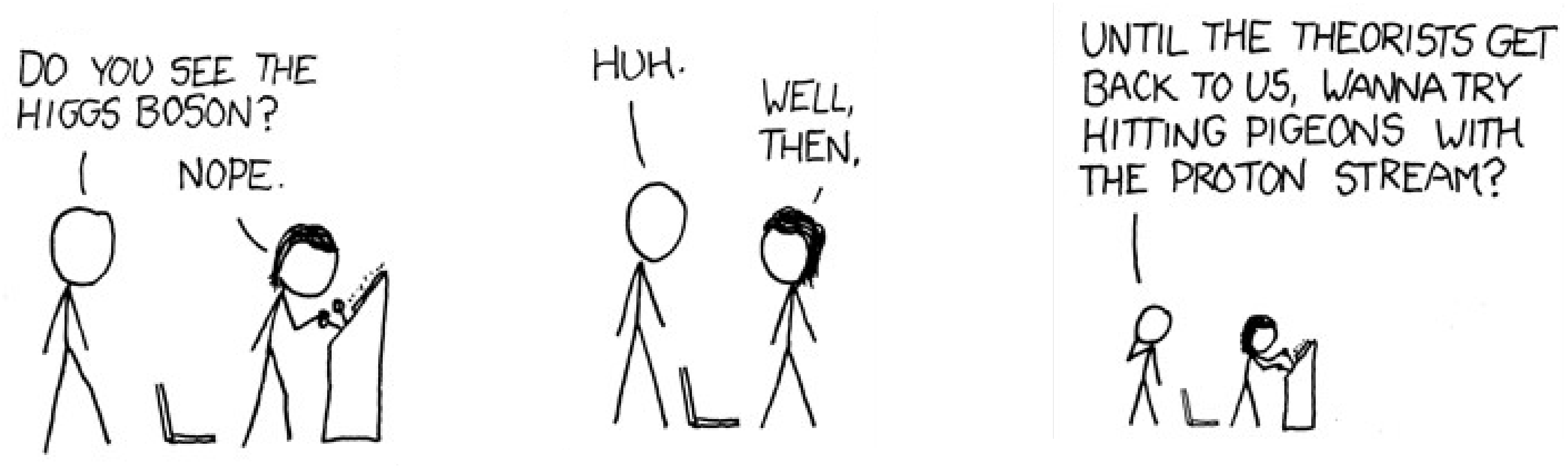
- The properties of a light Higgs in these scenarios can differ radically from those expected in the SM.
- Leads to unusual signature patterns at the LHC.

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

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.

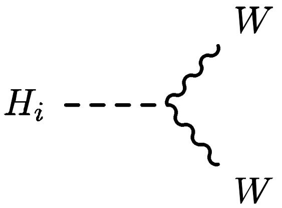


[cartoon from xkcd.com]

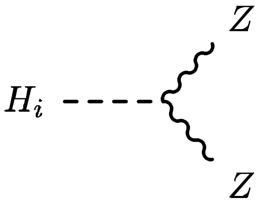
Effective Couplings from Non-Minimal Higgs Sectors

- 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

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

Mixing between mass, gauge eigenstates: C$_S$

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 parameterize them using coefficients $\eta_{W,Z}$ and η_{f_i} [Phalen, Thomas, Wells].

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

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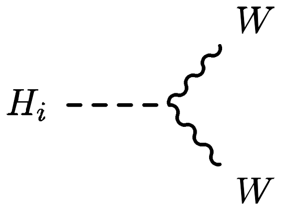

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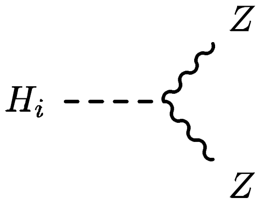

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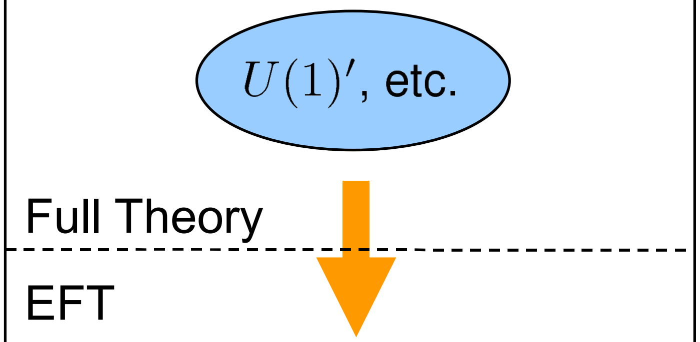
Generally not universal

Case Study: the Lepton-Specific Higgs

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

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



$U(1)'$, etc.

Full Theory

EFT

$\mathbb{Z}_2$ Parity Assignments:

Even: ϕ_q, q, u, d, ℓ

Odd: ϕ_ℓ, e

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

Higgs Potential

$$\begin{aligned} V &= \tfrac{1}{2}\lambda_1(\phi_q^\dagger\phi_q)^2 + \tfrac{1}{2}\lambda_1(\phi_\ell^\dagger\phi_\ell)^2 + \lambda_3(\phi_q^\dagger\phi_q)1(\phi_\ell^\dagger\phi_\ell) \\ &\quad + \lambda_4(\phi_q^\dagger\phi_\ell)1(\phi_\ell^\dagger\phi_q) + \lambda_5\left[(\phi_q^\dagger\phi_\ell)(\phi_q^\dagger\phi_\ell) + h.c.\right] \\ &\quad + m_{\phi_q}^2\phi_q^\dagger\phi_q + m_{\phi_\ell}^2\phi_\ell^\dagger\phi_\ell \end{aligned}$$

- If the $\mathbf{Z}_2$ symmetry is broken softly, all scalar mass eigenstates (the pseudoscalar Higgs) obtain masses.

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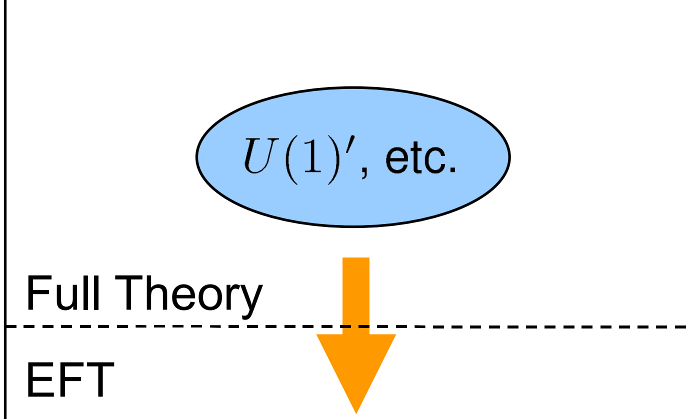

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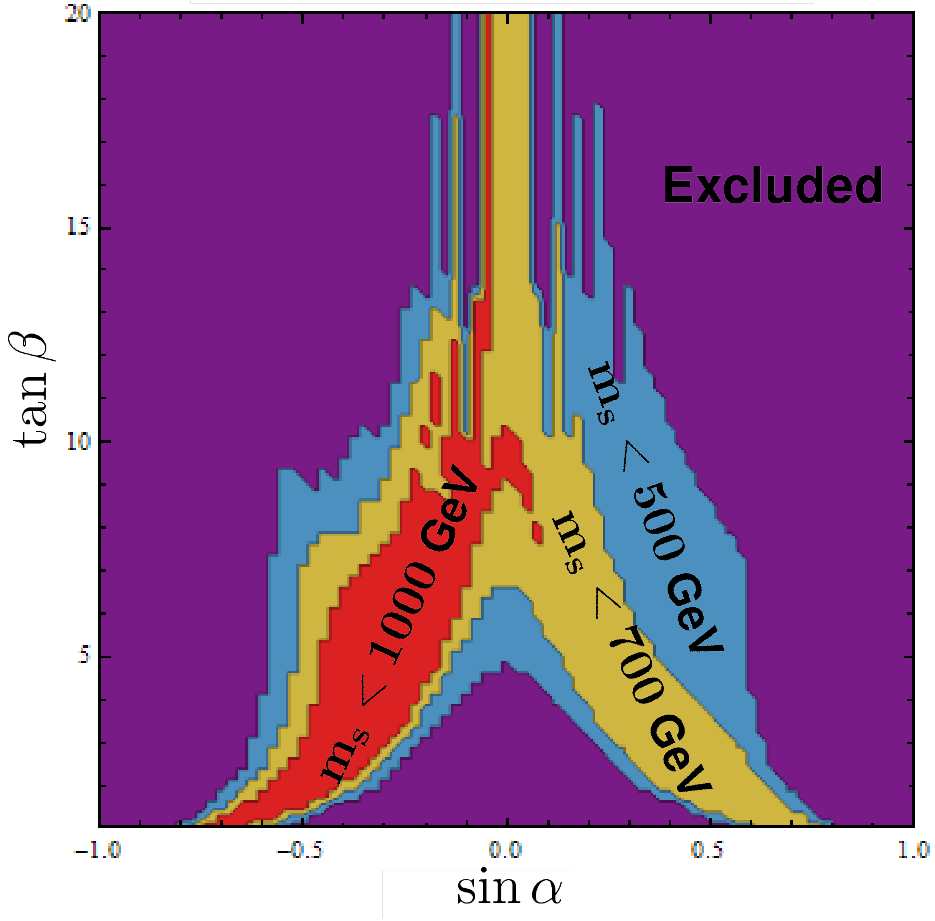
Coupling Modifications

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

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

Perturbativity Constraints

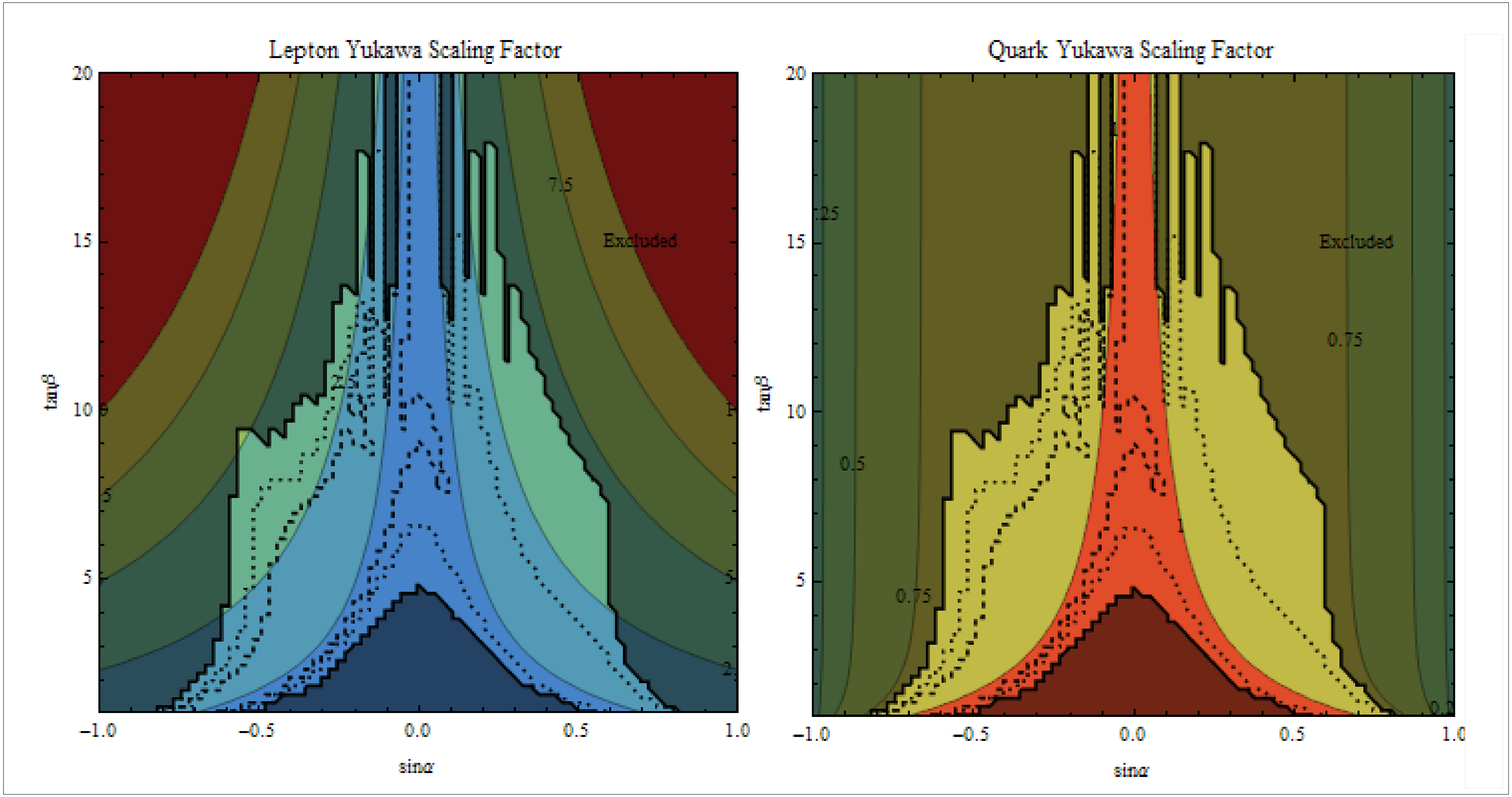


$$\eta_q = \frac{\cos\alpha}{\sin\beta} \qquad \eta_\ell = -\frac{\sin\alpha}{\cos\beta}$$

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

- In a 2HDM, the η parameters are functions of only two angles α and β.
- Not all of $\{\alpha, \beta\}$ parameter space is allowed, however, because of perturbativity and vacuum stability constraints on the λ_i.
- Example: in the decoupling limit, where $m^2_{H^0}, m^2_A, m^2_{H^\pm} \to \infty$, $\alpha \approx \beta - \pi/2$.

Constraints: Perturbativity



- Perturbativity of the λ_i places constraints on the parameter space.
- For a typical point, η_q, $\eta_{w,Z}$ remain close to 1, η_ℓ is augmented by an $\mathcal{O}(1)$ factor.

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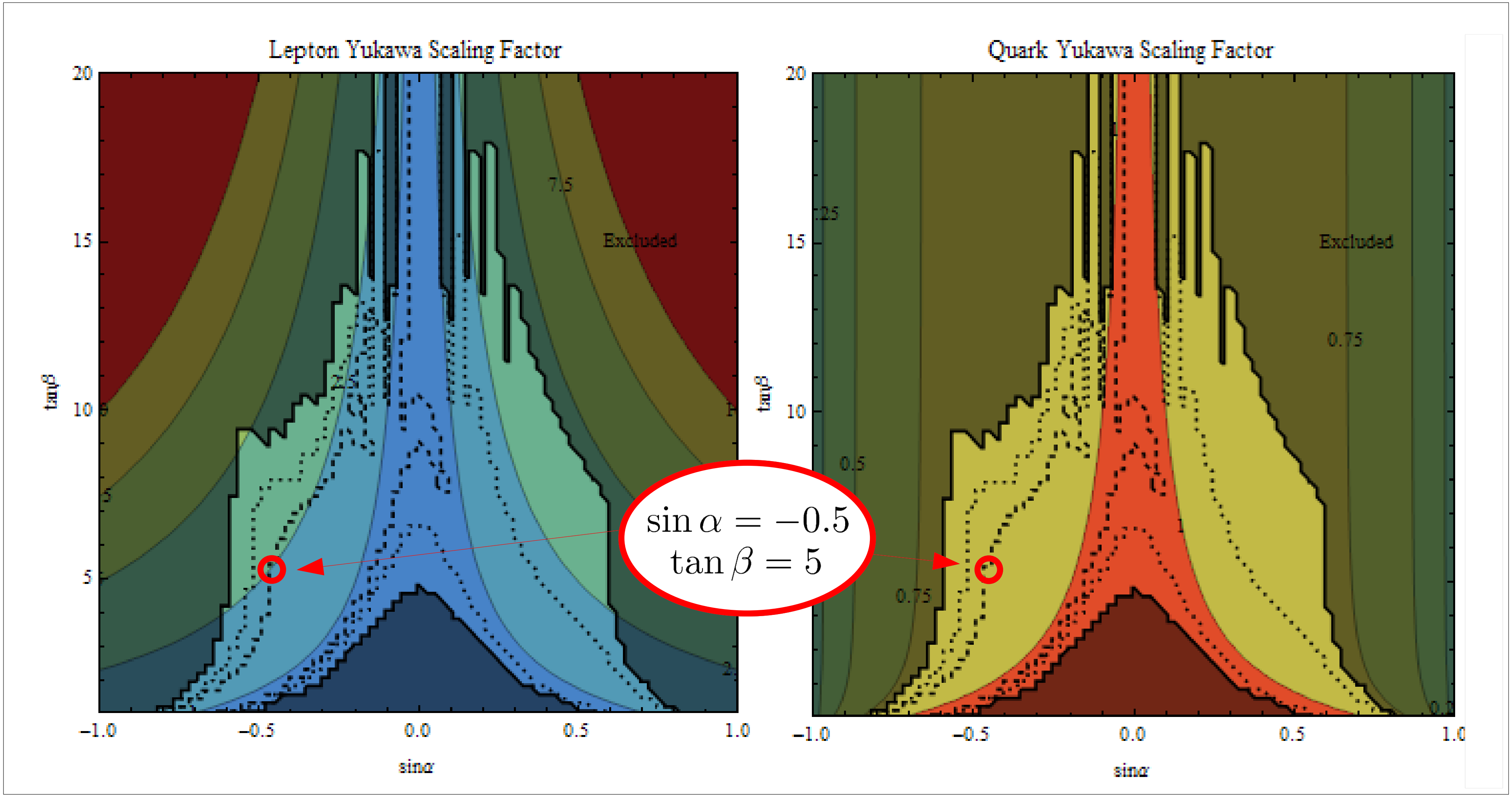

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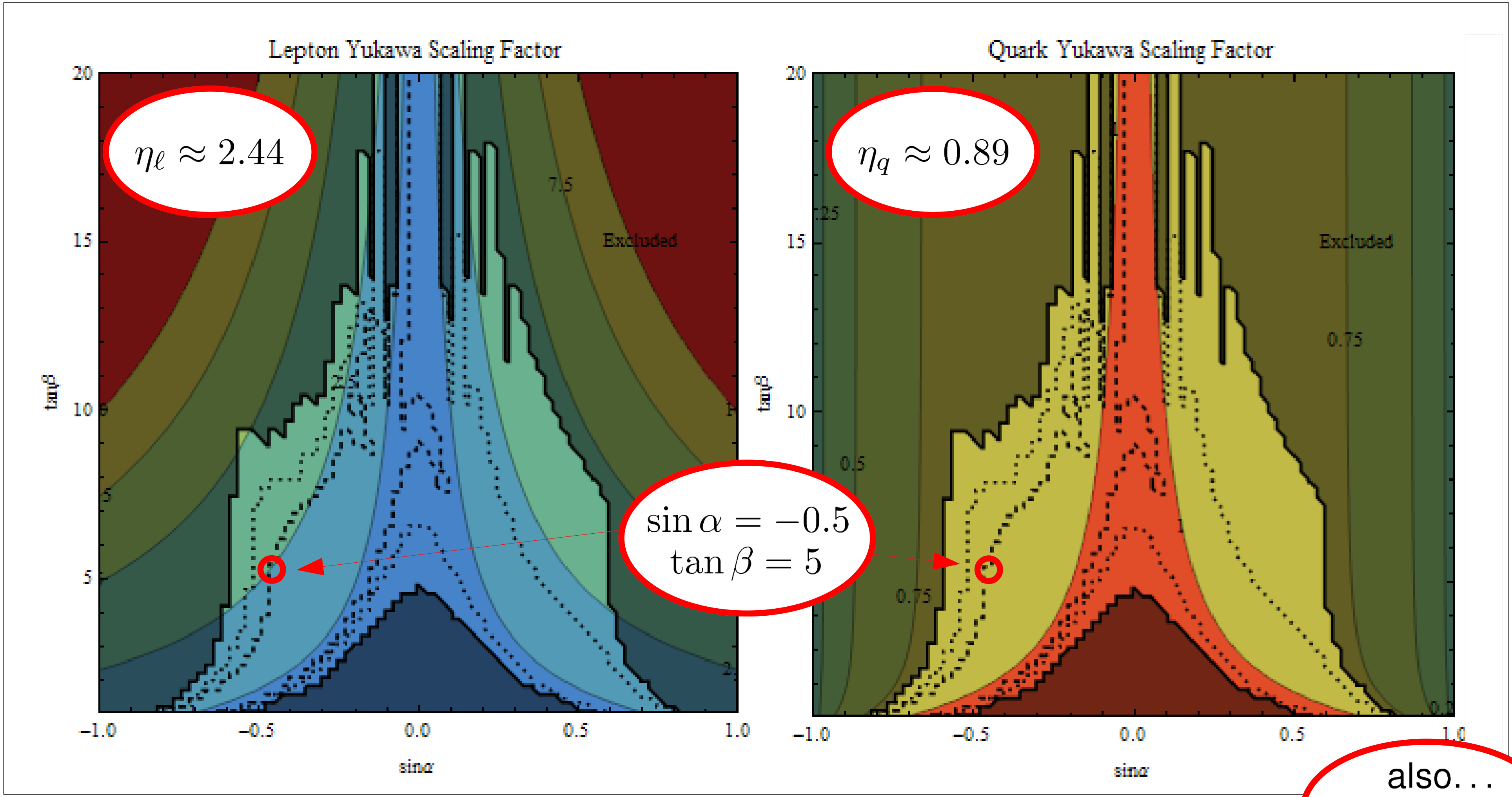

$\eta_\ell \approx 2.44$

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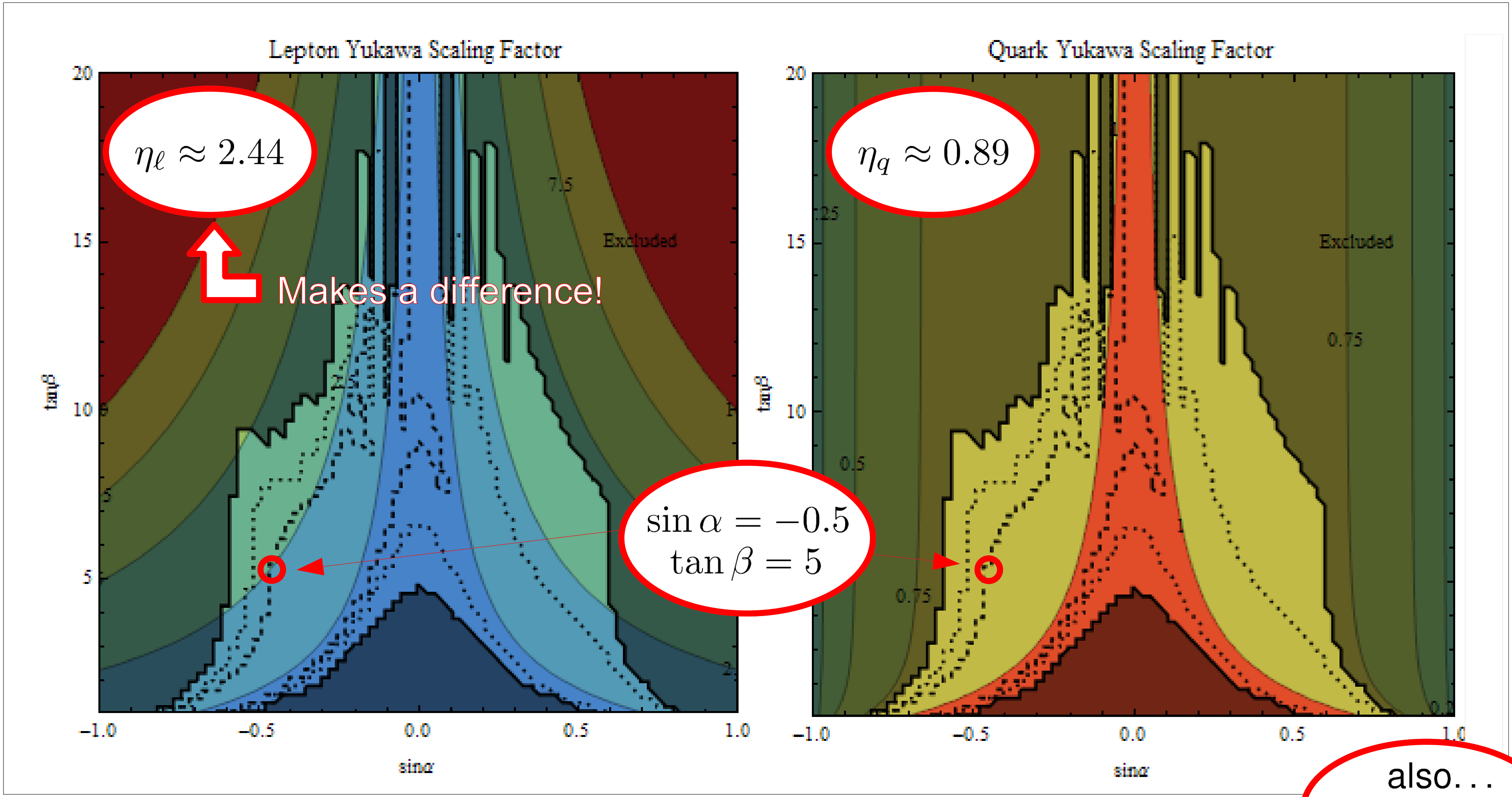

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Makes a difference!

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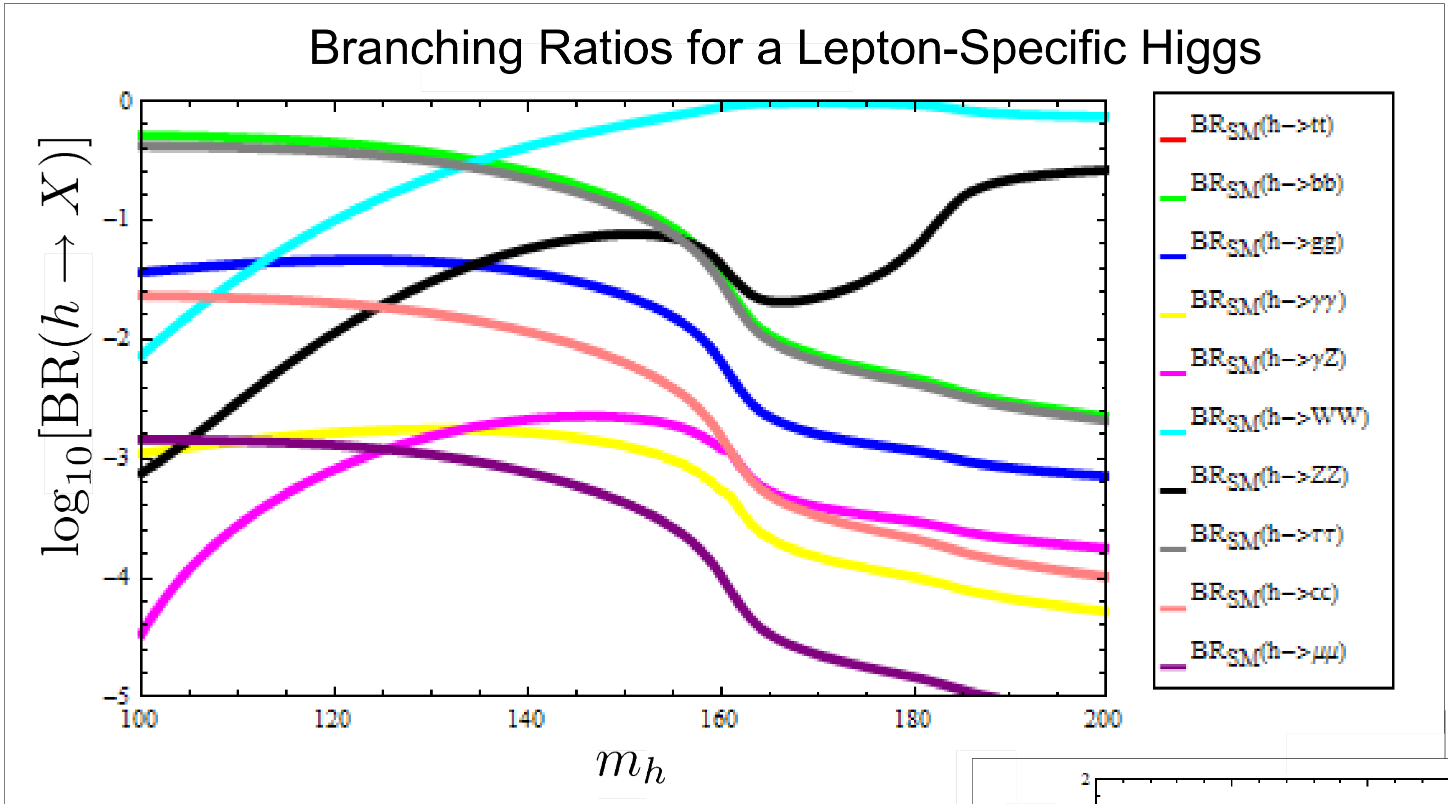
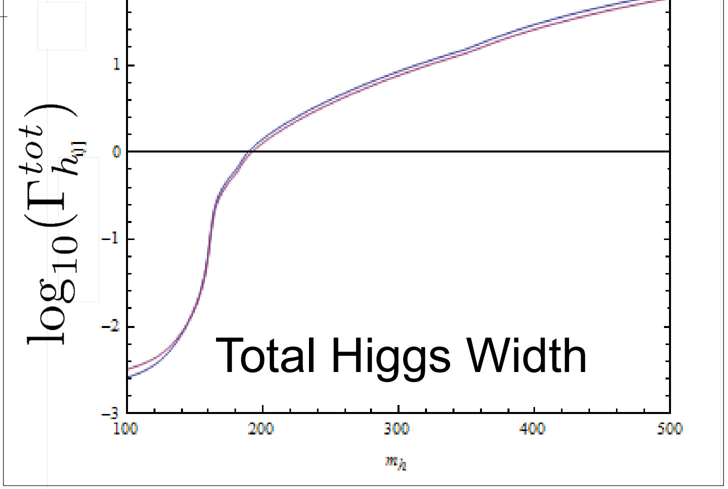
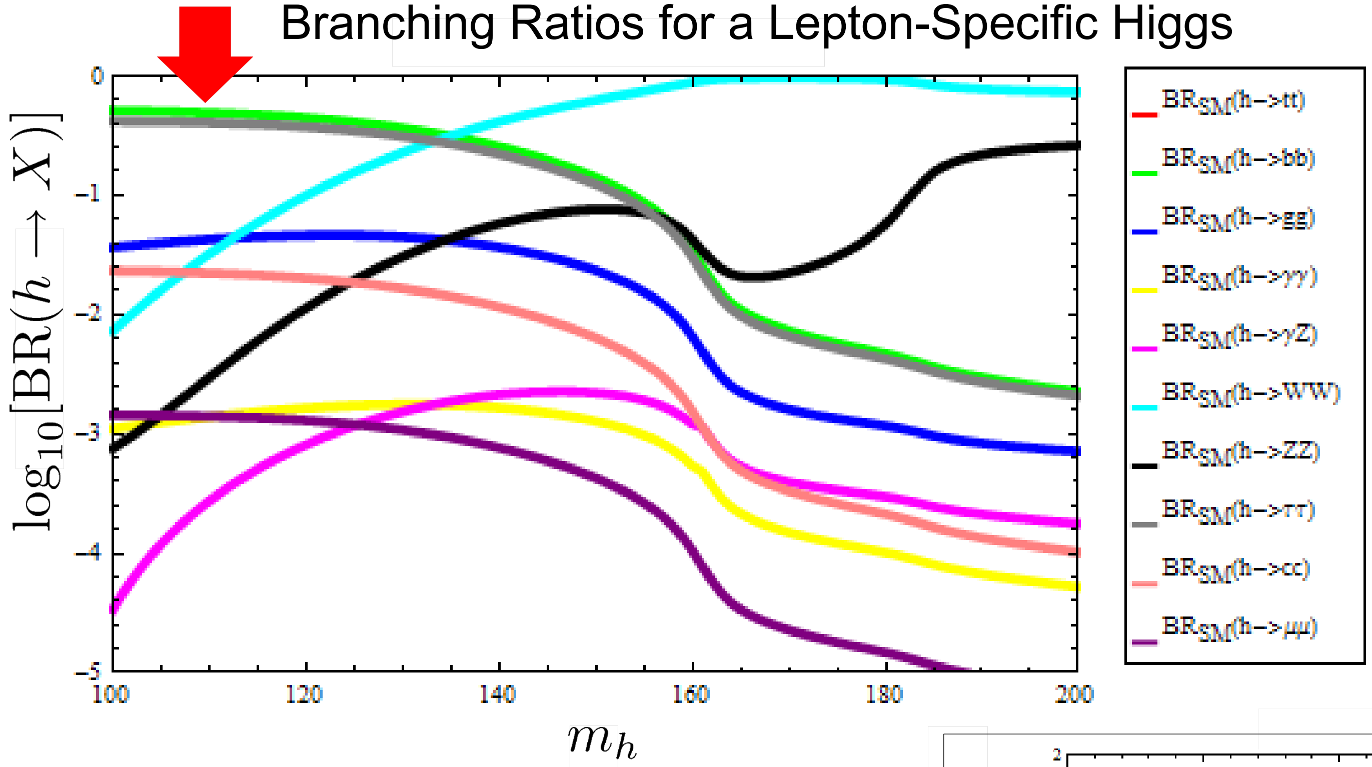




- Branching ratios for Higgs decays into leptons are substantially increased.
- $\Gamma_h^{tot} \approx \Gamma_h^{SM,tot}$, hence the narrow-width approximation is justified.

$h \to \tau^+\tau^-$ enhanced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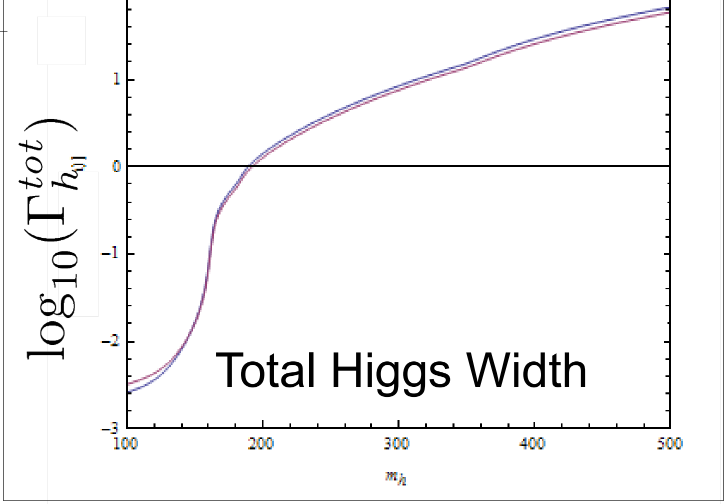
Total Higgs Width

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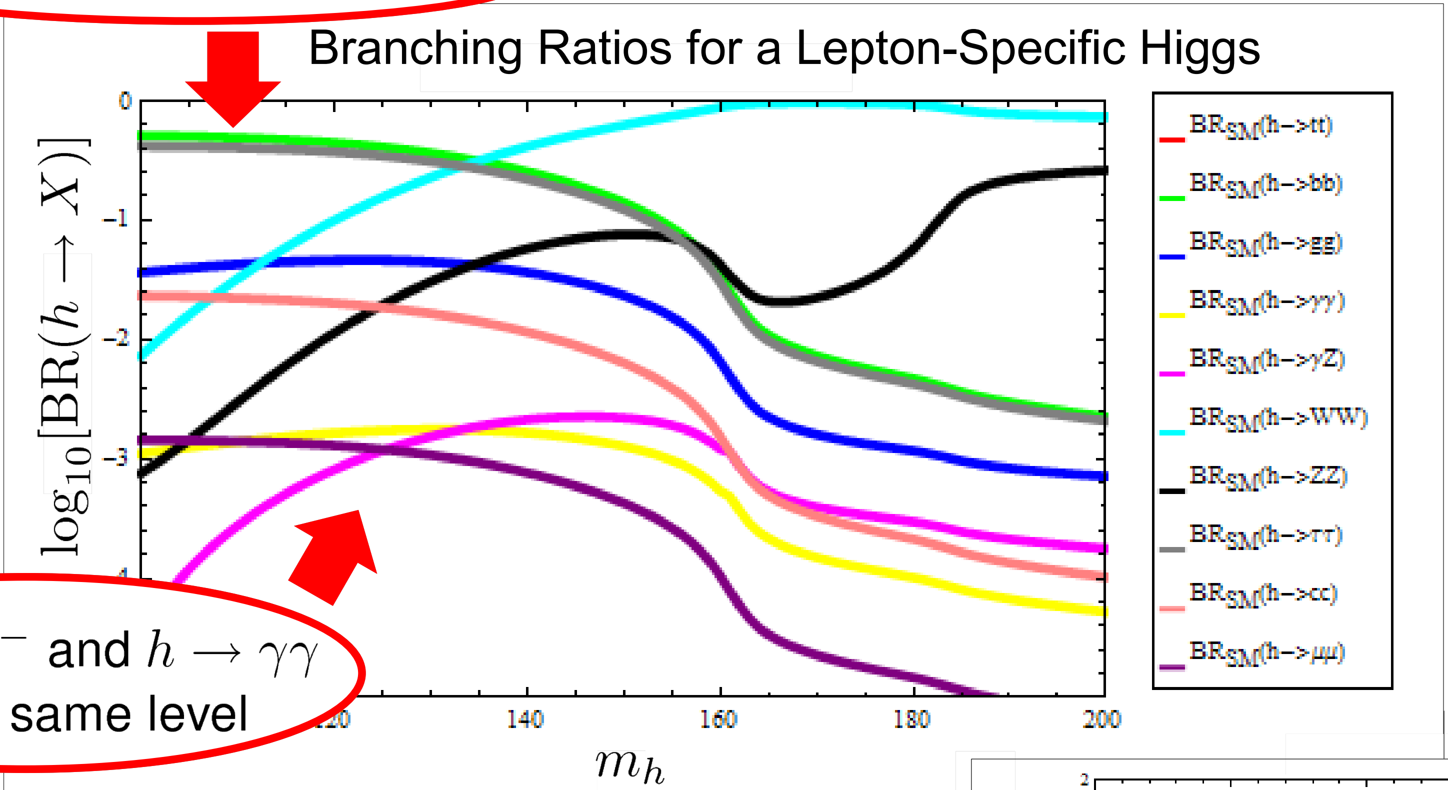
Branching Ratios for a Lepton-Specific Higgs

$h \to \mu^+\mu^-$ and $h \to \gamma\gamma$
on the same level

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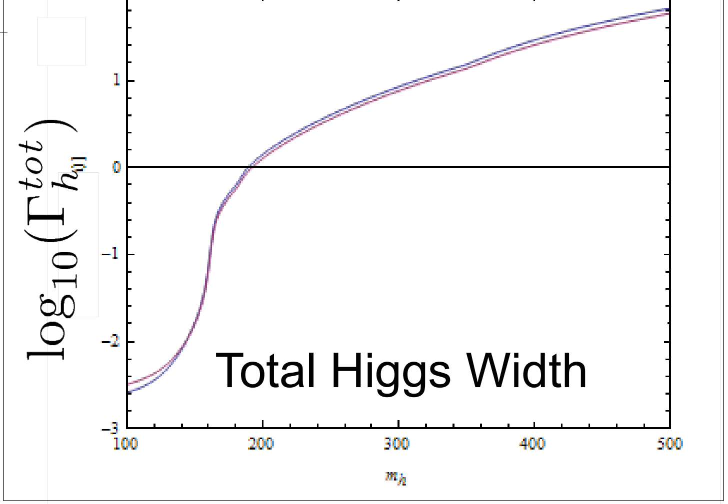

Total Higgs Width

The Effect on Observables

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

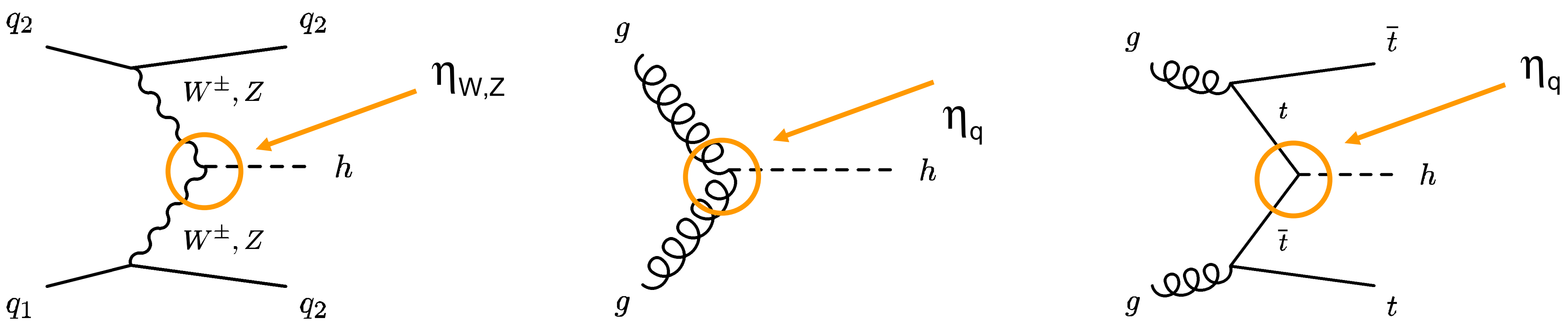
3). Modification of Total Higgs Width

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

1). Modification of Production Cross Section

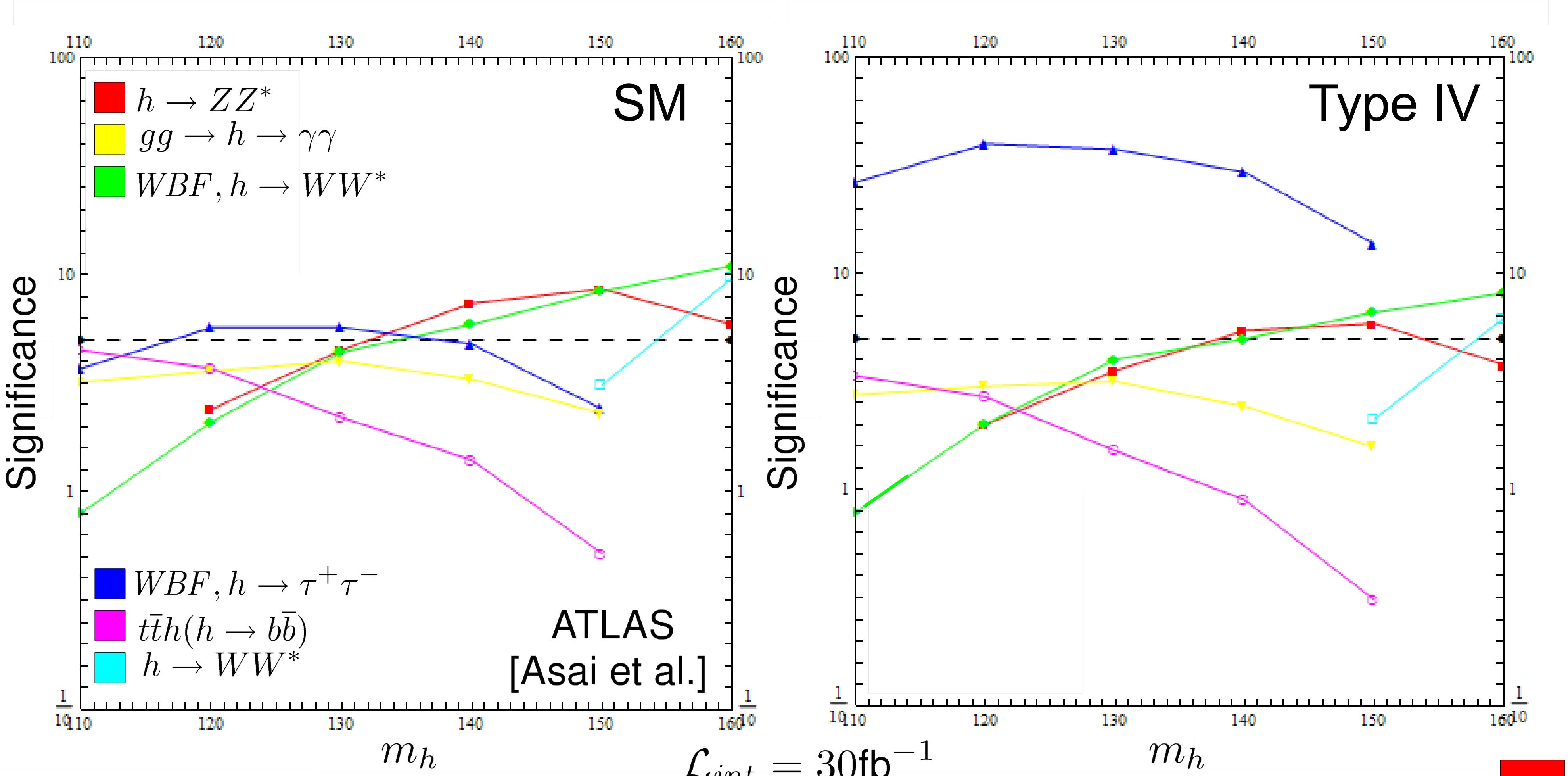
2). Modification of Decay Widths

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



Discovering a Type IV Higgs

- Most of the usual discovery channels for an SM Higgs are suppressed; the significance of the WBF, $h \to \tau\tau$ channel is dramatically amplified.



$\mathcal{L}_{int} = 30\text{fb}^{-1}$

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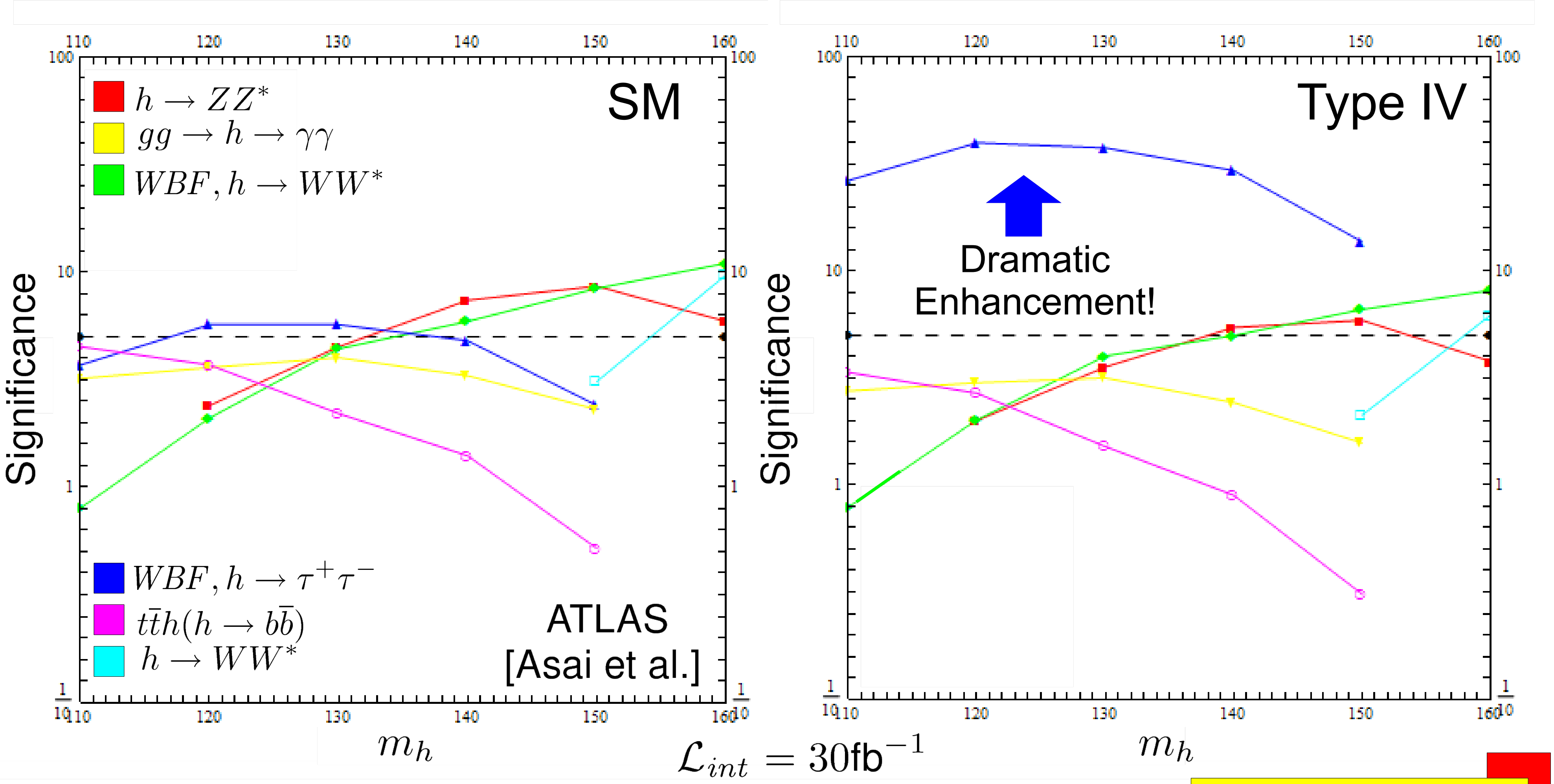
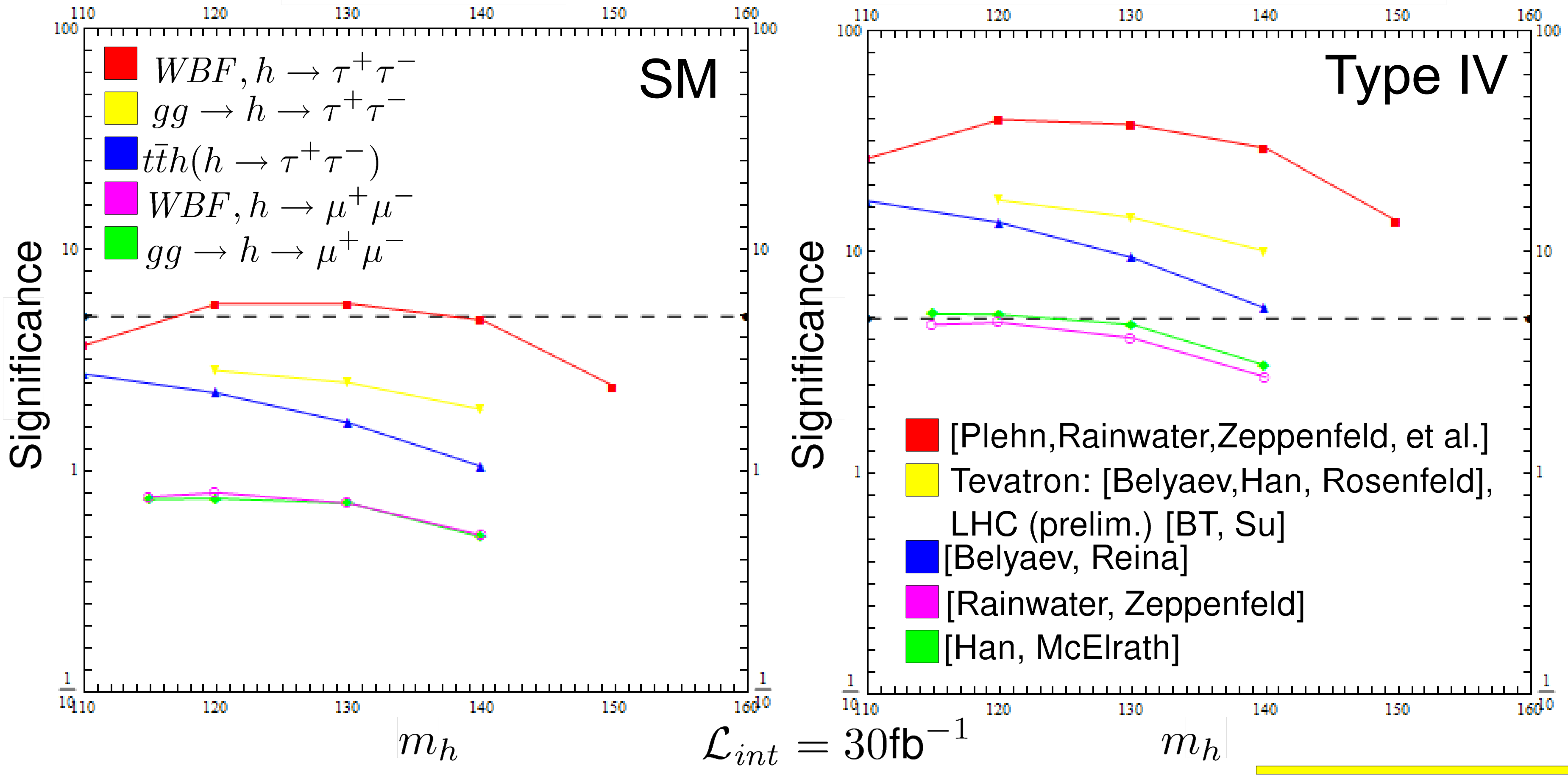


Leptonic Discovery Channels

- 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.



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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 lepton-specific Higgs scenario, final states involving Higgs decays to leptons provide clean signatures for Higgs discovery.