Interpreting Higgs Results from Natural Physics

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arXiv:1202.3144

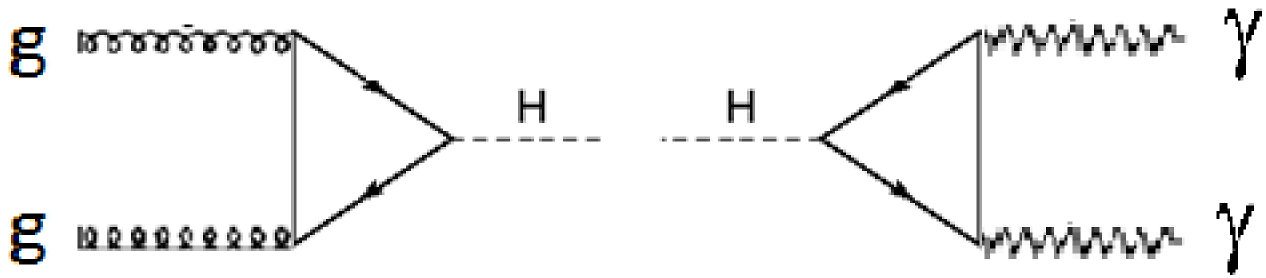
Outline

- Naturalness vs. Discovery
- Higgs at the LHC
- Constraints on BSM physics

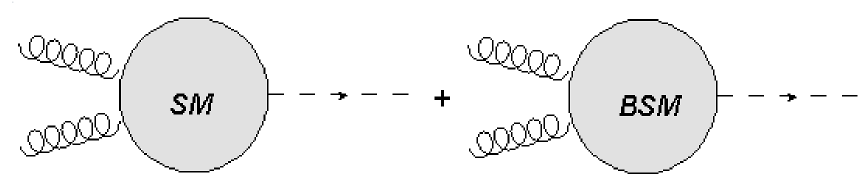
The Higgs is an excellent tool to study new physics and hierarchy problem

Learning from the Higgs

- Discovering the Higgs is a loop-effect



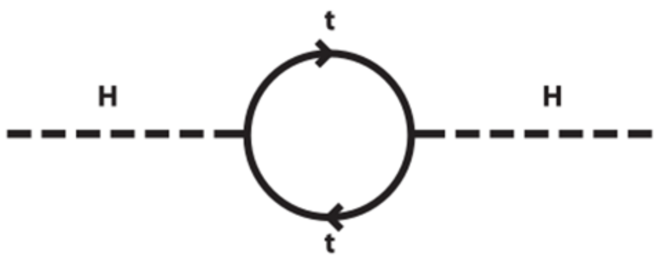
- No additional loop suppression to see new physics



- Very sensitive to new physics

Chronic Hierarchy Problem Slide

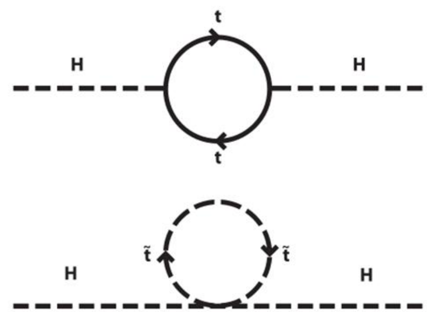
- **Hierarchy Problem**
  - Why is the weak force so much stronger than gravity?
- **Higgs Naturalness**
  - Why is this scale stable?
  - Quantum corrections should push the Higgs vev and the EW-scale to the UV-scale.

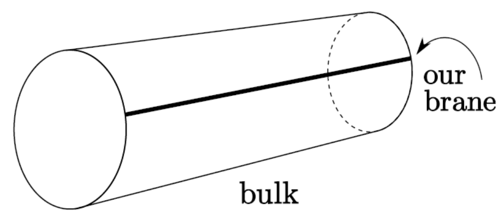


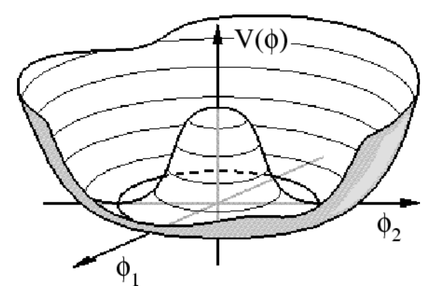
$$\delta m_h^2 = \frac{3 m_t^2}{2\pi^2 v^2} \Lambda^2$$

Solutions to the Hierarchy Problem

- Standard Model → New effective theory at the TeV scale
  - Supersymmetry
    - Weakish scale soft-SUSY breaking masses
  - Extra Dimensions
    - ADD, RS, …
  - Strong Dynamics
    - Technicolor, Little Higgs, …







Little Hierarchy Problem

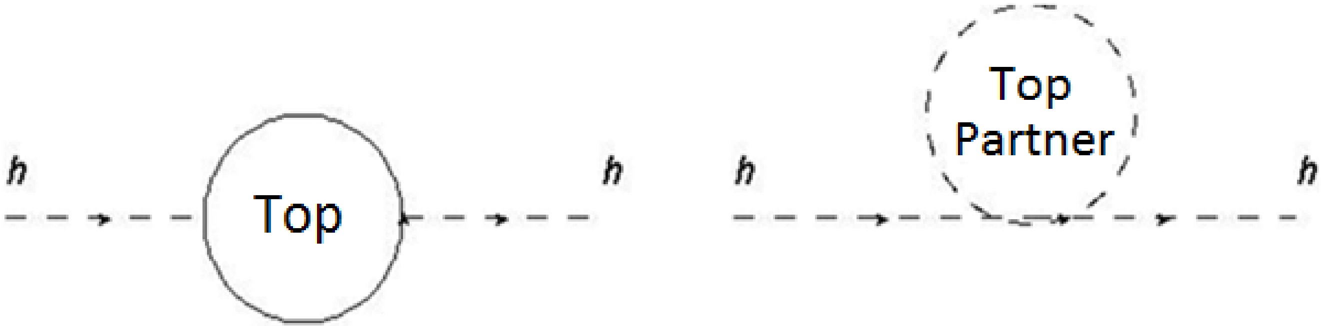
- Where is the new physics that was promised to me?
  - All these theories predict new physics at the TeV scale, then where is it?
  - Wasn’t low-energy supersymmetry coming from M-Theory compactified on a G2-manifold supposed to be discovered before I graduated?

Higgs Discovery vs. Hierarchy Problem

- In fact, the cancellation of the Higgs' mass divergence and the production and decay are profoundly related.

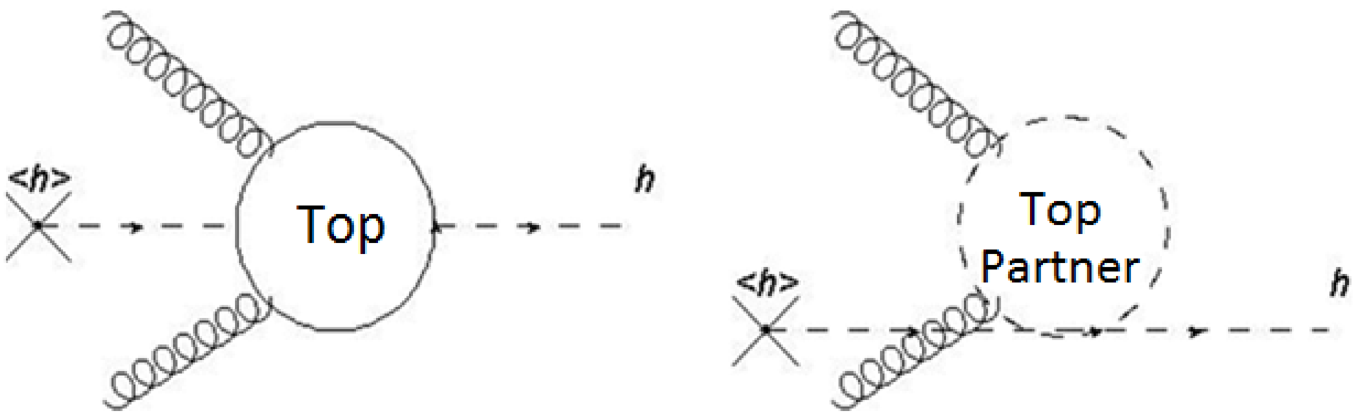
- Precision Higgs is telling us how natural our world is.

Dermisek, Low, 0701235
Low, Rattazzi, Vichi, 0907.5413
Arvanitaki, Villadoro, 1112.4835



Top partners cancel Λ^2 divergence

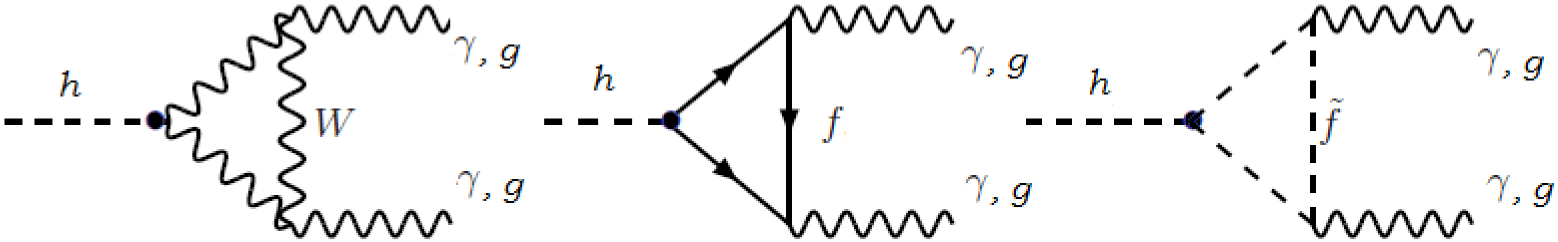
Top partners—particles that make the Higgs mass natural—are colored/charged



Changes Higgs rates.

With the same couplings

Technical Details



- $\Gamma(h \to \gamma\gamma) =$
  $$\frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3}\left| g_{hVV} A_1(\tau_V) + N_c Q_f^2 g_{hff} A_{\frac{1}{2}}(\tau_f) + N_c Q_f^2 \frac{g_{h\tilde{f}\tilde{f}}}{m_{\tilde{f}}{}^2} A_0(\tau_{\tilde{f}}) \right|^2$$
  $$\tau_i = m_h^2/4m_i^2$$

For $\tau_i \to 0$ $\quad A_1(\tau_V) \to -7 \quad A_{\frac{1}{2}}(\tau_f) \to \frac{4}{3} \quad A_0(\tau_{\tilde{f}}) \to \frac{1}{3}$

  - In the SM, the W-boson dominates, but the top deconstructively interferes
  - Fermions contribute 4 times greater (same as the beta function)
  - $g_{hff} = 1$ for fermions getting their mass from the Higgs vev, but $g_{hff} = \lambda_{hff} v/\sqrt{2} m_f$ for vector-like fermion

- $\Gamma(h \to gg) = \frac{3 G_F \alpha_s^2 M_h^3}{192\sqrt{2}\pi^3}\left| g_{hff} A_{\frac{1}{2}}(\tau_f) + \frac{g_{h\tilde{f}\tilde{f}}}{m_{\tilde{f}}{}^2} A_0(\tau_{\tilde{f}}) \right|^2$
  - In the SM, the top dominates.

The Higgs Hunter's Guide
Djouadi, 0503173

Less Technical Details

Largest contribution

$$\Gamma(h \to \gamma\gamma) = |W - top \mp T|^2$$

Interference-
20% of the
W-boson
contribution

$$\Gamma(h \to gg) = |top \pm T|^2$$

New physics will increase one, while decreasing the other.

Ellis, Gaillard, Nanopoulos, 1976
Shifman, Vainshtein, Voloshin, Zakharov 1979
Dermisek, Low, 0701235

Changing the Rates

- In the limit $\frac{m_h^2}{4m_T^2} \to 0$ (integrating out heavy top partners), we can relate the loop to the coefficient of the $hF_{\mu\nu}F^{\mu\nu}$ operator from the QCD beta-function

  - Turn on a background Higgs and calculate the threshold effects from the Top partner

$$-\frac{1}{4g^2(\mu)}F_{\mu\nu}F^{\mu\nu} = -\frac{1}{4}\left(\frac{1}{g_\Lambda^2} - \frac{b_0}{16\pi^2}\log\frac{\Lambda^2}{\mu^2} - \frac{b_T}{16\pi^2}\log\frac{M_T^2(h)}{\mu^2} - \ldots\right)F_{\mu\nu}F^{\mu\nu}$$

  - The coefficient coefficient of the $hF_{\mu\nu}F^{\mu\nu}$ operator is proportional to

$$b_T \frac{1}{M_T^2(h)} \frac{\partial M_T^2(h)}{\partial h}\Bigg|_{h=v/\sqrt{2}}$$

Cancelling the Divergence

- Cancellation of the quadratic divergence is given in terms of Coleman–Weinberg effective potential Coleman, Weinberg 1973

$$V_{eff} = \frac{1}{32\pi^2}\Lambda^2 STrM^2(h) + \ldots$$

$$b_T \frac{1}{M_T^2(h)} \frac{\partial M_T^2(h)}{\partial h}\bigg|_{h=v/\sqrt{2}} \quad \Longleftrightarrow \quad STrM^2(h)$$

Combination

- Combine ATLAS and CMS
  - Repeat the analyses - compute and combine the likelihood functions for the best-fit values of the rates

$$R = \sigma\, Br \,/\, [\sigma\, Br]_{SM}$$

  - Use signal and background modeling from experiment, otherwise simulate the data.
  - Focus on the channels which observe a clear excess:

Channels

- 4 Lepton

$$R_V \equiv \frac{\sigma_{pp\to h} Br_{h\to ZZ^*}}{[\sigma_{pp\to h} Br_{h\to ZZ^*}]_{SM}} \simeq \frac{\Gamma_{h\to gg} Br_{h\to ZZ^*}}{[\Gamma_{h\to gg} Br_{h\to ZZ^*}]_{SM}}$$

- Di-photon (gluon fusion)

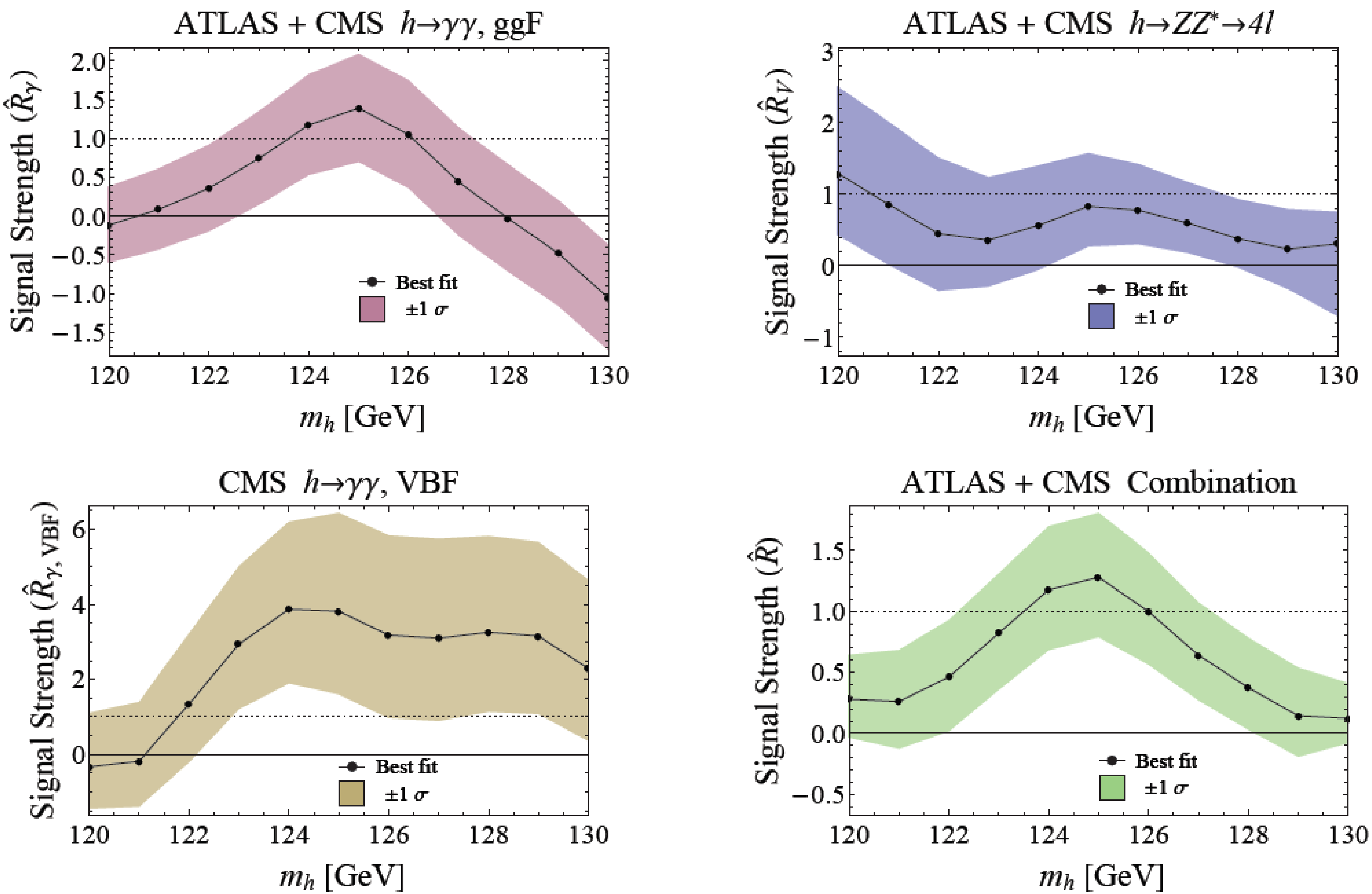
$$R_\gamma \equiv \frac{\sigma_{pp\to h} Br_{h\to \gamma\gamma}}{[\sigma_{pp\to h} Br_{h\to \gamma\gamma}]_{SM}} \simeq \frac{\Gamma_{h\to gg} Br_{h\to \gamma\gamma}}{[\Gamma_{h\to gg} Br_{h\to \gamma\gamma}]_{SM}}$$

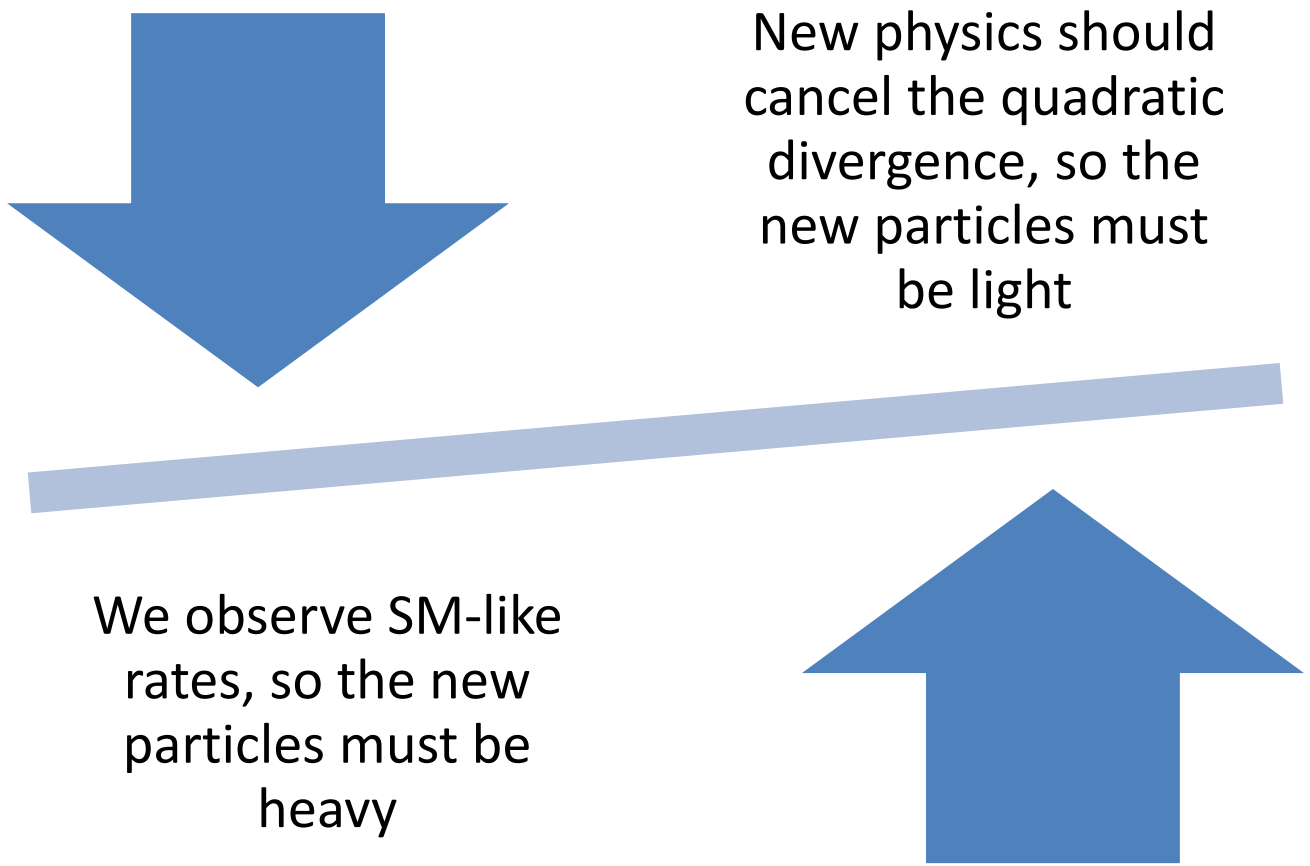
- Di-photon (vector boson fusion)

$$R_{\gamma,VBF} \equiv \frac{\sigma_{pp\to hjj} Br_{h\to \gamma\gamma}}{[\sigma_{pp\to hjj} Br_{h\to \gamma\gamma}]_{SM}} \simeq \frac{\Gamma_{h\to WW} Br_{h\to \gamma\gamma}}{[\Gamma_{h\to WW} Br_{h\to \gamma\gamma}]_{SM}}$$

With smaller gluon-fusion component

Constraints





More little hierarchy problems

will become stronger with more data

Formalism

- Effective theory (below the top mass)

$$\mathcal{L}_{eff} = c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b}b - c_\tau \frac{m_\tau}{v} h\, \bar{\tau}\tau + c_g \frac{\alpha_s}{12\pi v} h\, G^a_{\mu\nu} G^a_{\mu\nu} + c_\gamma \frac{\alpha}{\pi v} h\, A_{\mu\nu} A_{\mu\nu} \,.$$

In the Standard Model

$$c_{V,\mathrm{SM}} = c_{b,\mathrm{SM}} = 1 \,, \qquad c_{g,\mathrm{SM}} \simeq 1 \,, \qquad c_{\gamma,\mathrm{SM}} \simeq 2/9$$

Decay Widths of the Higgs

- Relative to the SM

$$\frac{\Gamma(h \to b\bar{b})}{\Gamma_{SM}(h \to b\bar{b})} = |c_b|^2, \qquad \frac{\Gamma(h \to WW^*)}{\Gamma_{SM}(h \to WW^*)} = \frac{\Gamma(h \to ZZ^*)}{\Gamma_{SM}(h \to ZZ^*)} = |c_V|^2,$$

$$\frac{\Gamma(h \to gg)}{\Gamma_{SM}(h \to gg)} \simeq |c_g|^2, \qquad \frac{\Gamma(h \to \gamma\gamma)}{\Gamma_{SM}(h \to \gamma\gamma)} = \left|\frac{\hat{c}_\gamma}{\hat{c}_{\gamma,SM}}\right|^2,$$

$$\begin{aligned}
R_V &\equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to ZZ^*)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to ZZ^*)} \simeq \left|\frac{c_g c_V}{c_b}\right|^2, \\
R_\gamma &\equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to \gamma\gamma)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to \gamma\gamma)} \simeq \left|\frac{c_g \hat{c}_\gamma}{\hat{c}_{\gamma,SM} c_b}\right|^2, \\
R_{\gamma,VBF} &\equiv \frac{\sigma(pp \to hjj)\mathrm{Br}(h \to \gamma\gamma)}{\sigma_{SM}(pp \to hjj)\mathrm{Br}_{SM}(h \to \gamma\gamma)} \simeq \left|\frac{c_V \hat{c}_\gamma}{\hat{c}_{\gamma,SM} c_b}\right|^2.
\end{aligned}$$

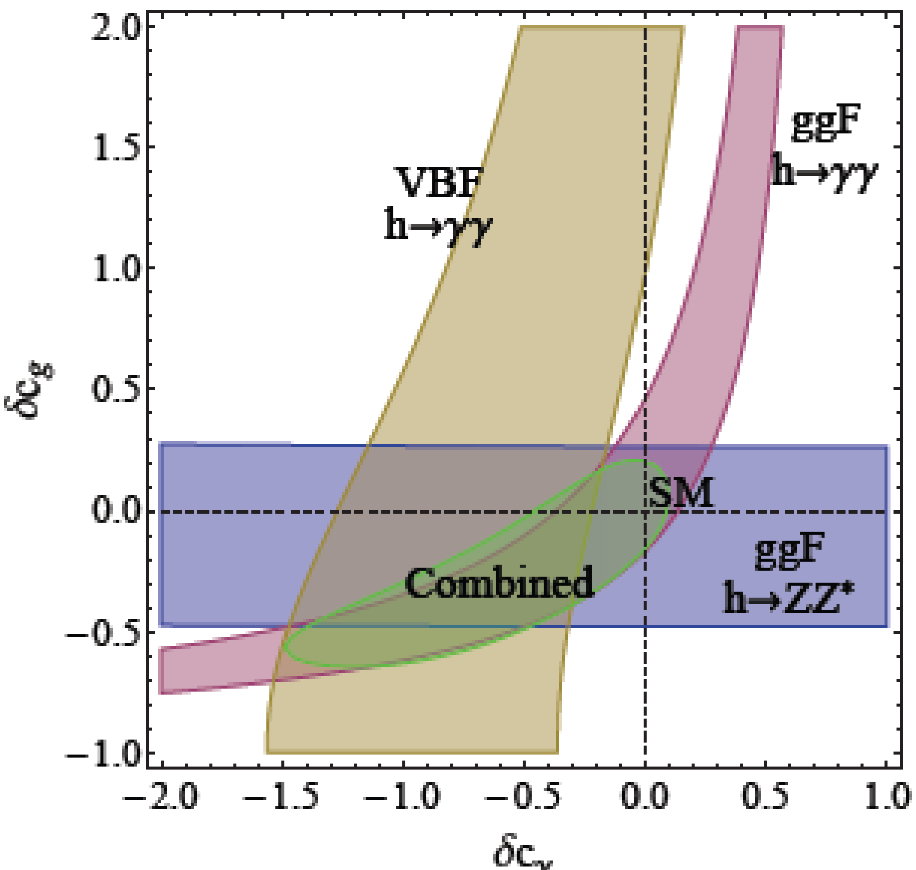
$$\mathcal{L}_{eff} = c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b}b - c_\tau \frac{m_\tau}{v} h\, \bar{\tau}\tau$$
$$+ c_g \frac{\alpha_s}{12\pi v} h\, G^a_{\mu\nu} G^a_{\mu\nu} + c_\gamma \frac{\alpha}{\pi v} h\, A_{\mu\nu} A_{\mu\nu} \, .$$

Giudice, Grojean, Pomarol, Rattazzi, **ph/0703164**
Espinosa, Grojean, Muhlleitner, Trott **1202.3697**
Azatov, Contino, Galloway, **1202.3415**

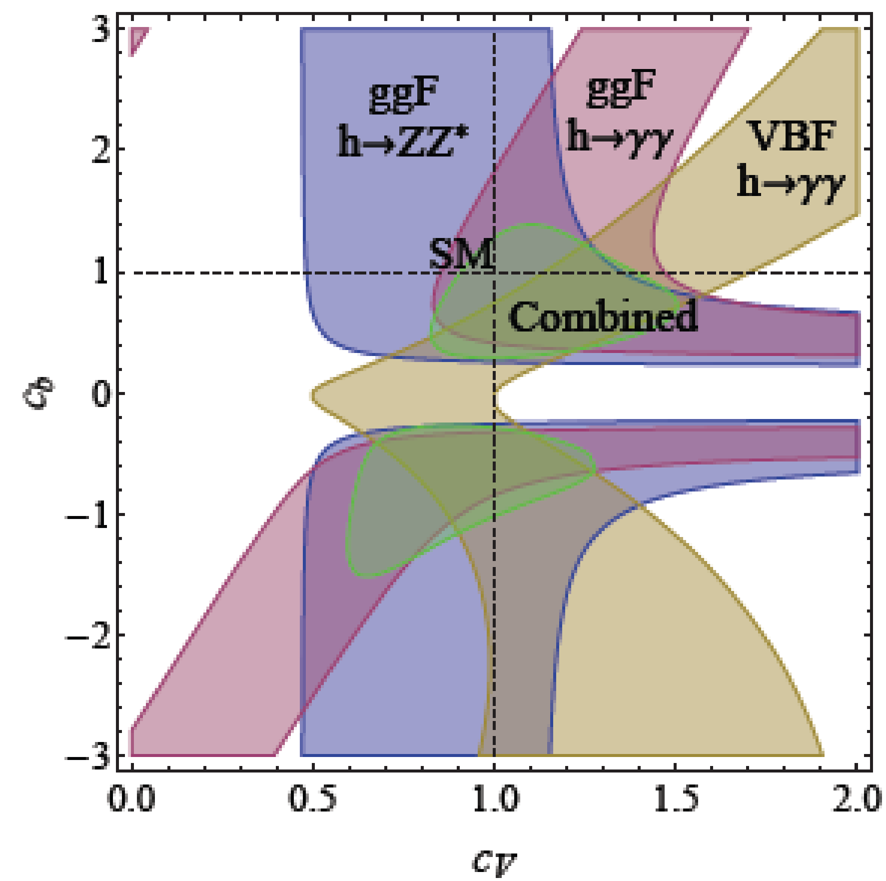
New particles in the loops

Strongly Interacting Light Higgs

$c_V = c_b = c_\tau = 1$

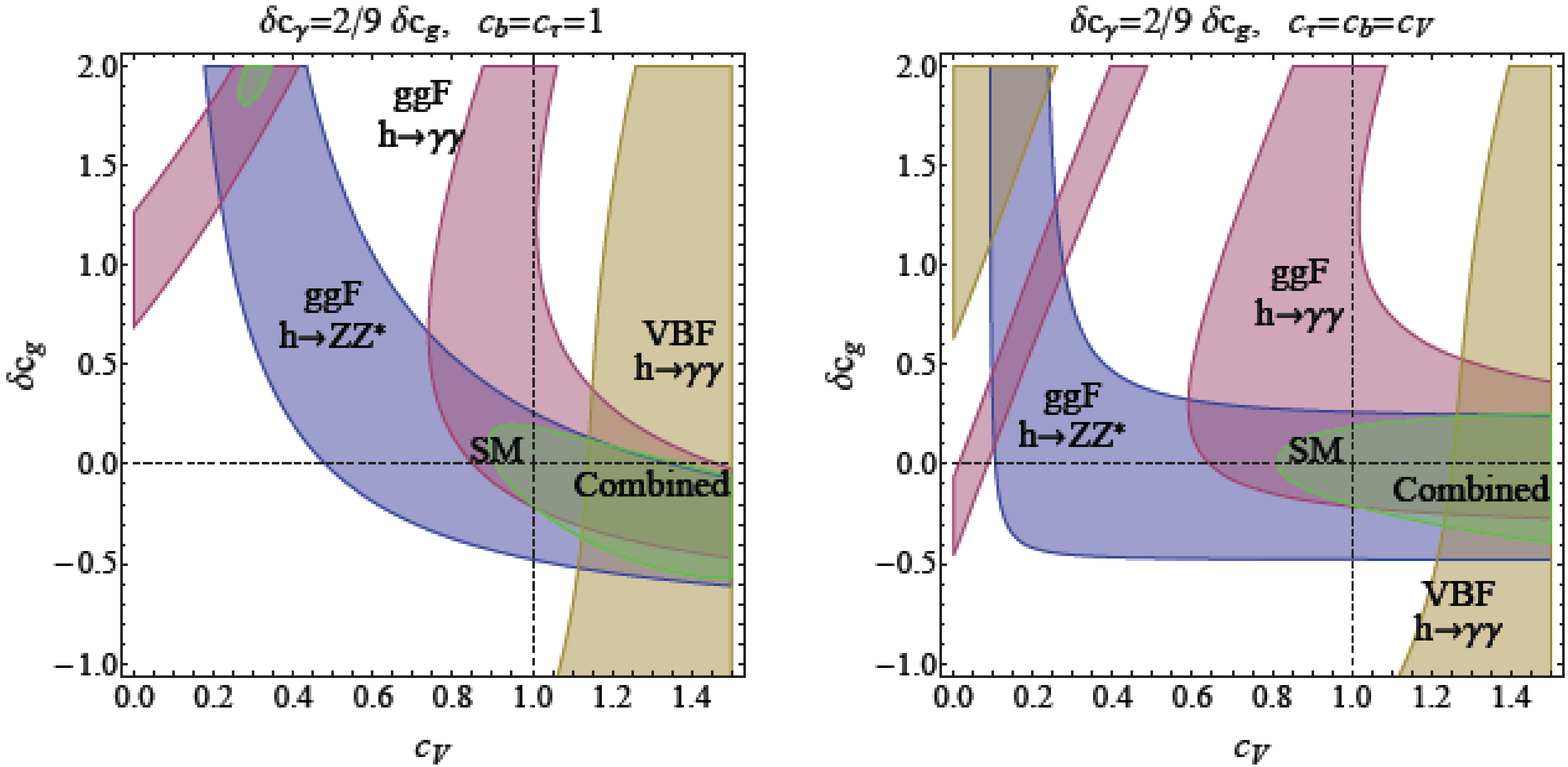


$c_b = c_\tau = c_g = 9/2 c_\gamma$



$$\mathcal{L}_{eff} = c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b}b - c_\tau \frac{m_\tau}{v} h\, \bar{\tau}\tau + c_g \frac{\alpha_s}{12\pi v} h\, G^a_{\mu\nu} G^a_{\mu\nu} + c_\gamma \frac{\alpha}{\pi v} h\, A_{\mu\nu} A_{\mu\nu} \,.$$

Top Partner models



Scalar Top Partner

$$b_T \frac{1}{M_T^2(h)} \frac{\partial M_T^2(h)}{\partial h}\bigg|_{h=v/\sqrt{2}} \quad \Longleftrightarrow \quad STrM^2(h)$$

- A single scalar partner

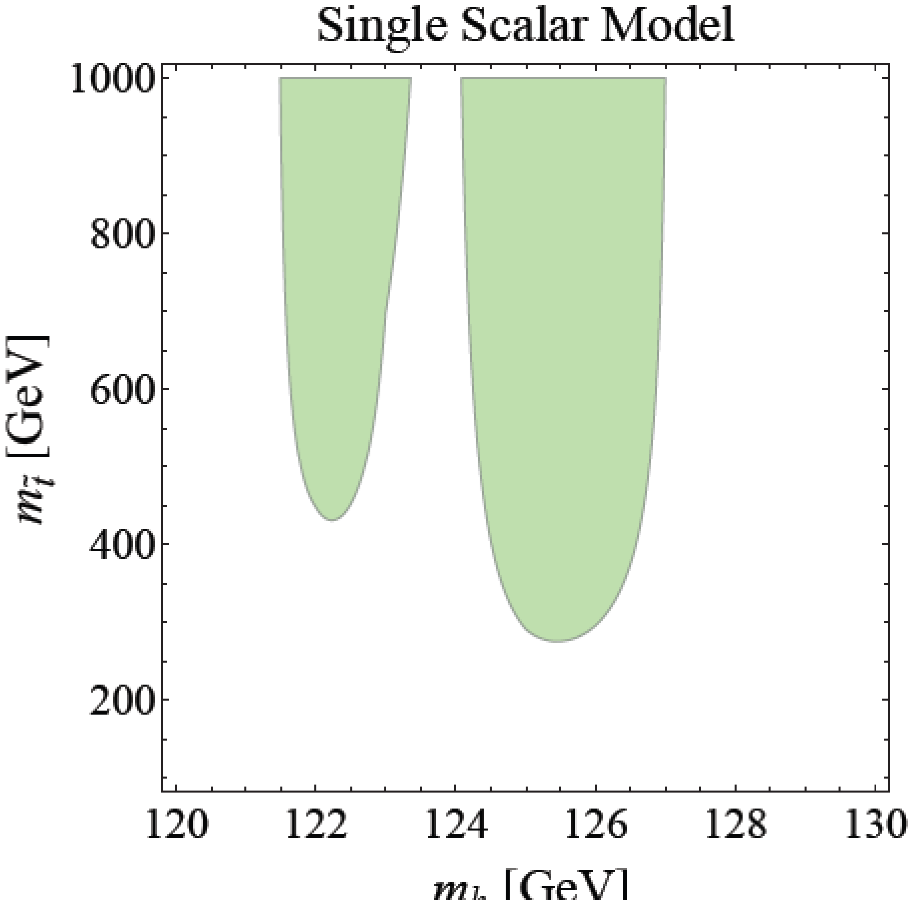
$$\mathcal{L}_{stop} = -\left(yHQt^c + \text{h.c.}\right) - |\tilde{t}|^2\left(M^2 + \lambda|H|^2\right)$$

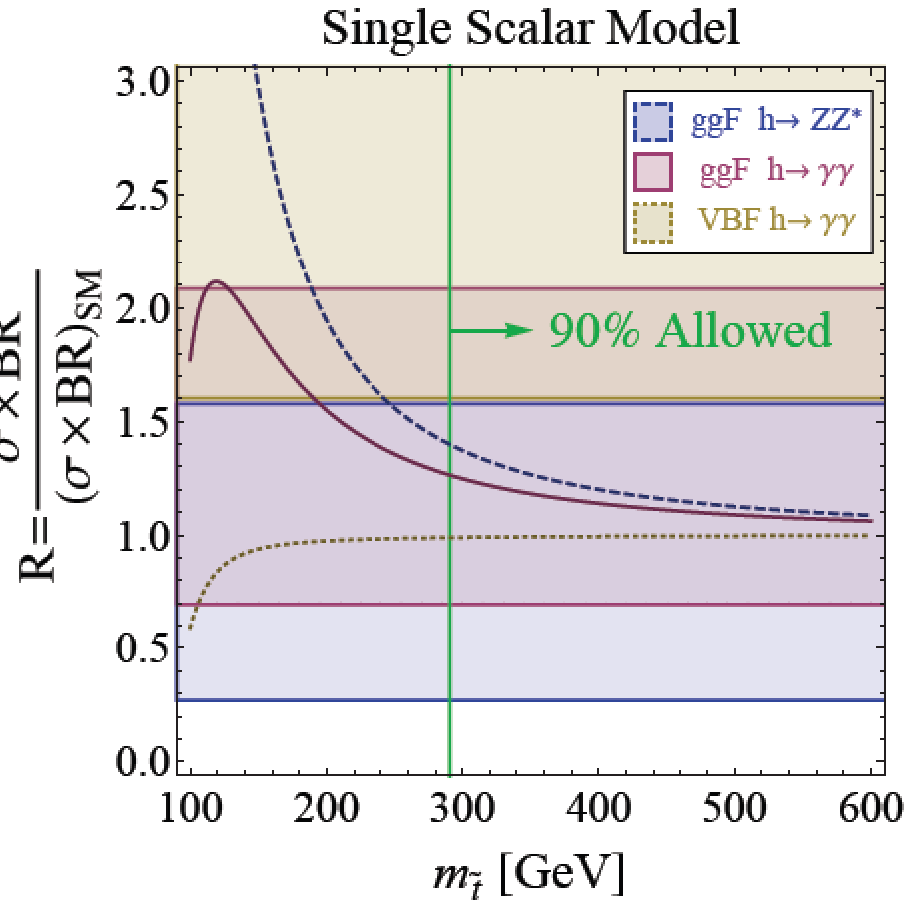
$$\lambda = 2y^2$$

will cancel quadratic divergence but contribute the same as the top to the rates.

$$\Lambda^2 \downarrow \qquad h \to gg \uparrow \qquad h \to \gamma\gamma \downarrow$$

Scalar Top Partner





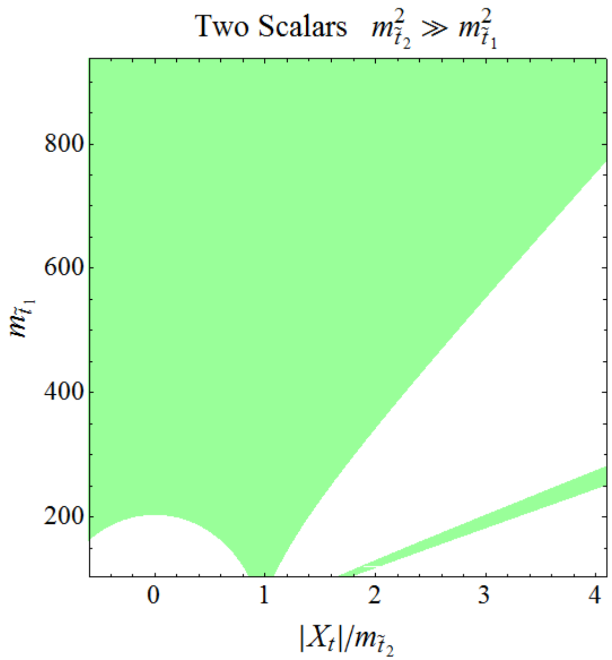
Two Scalar Top Partners - SUSY

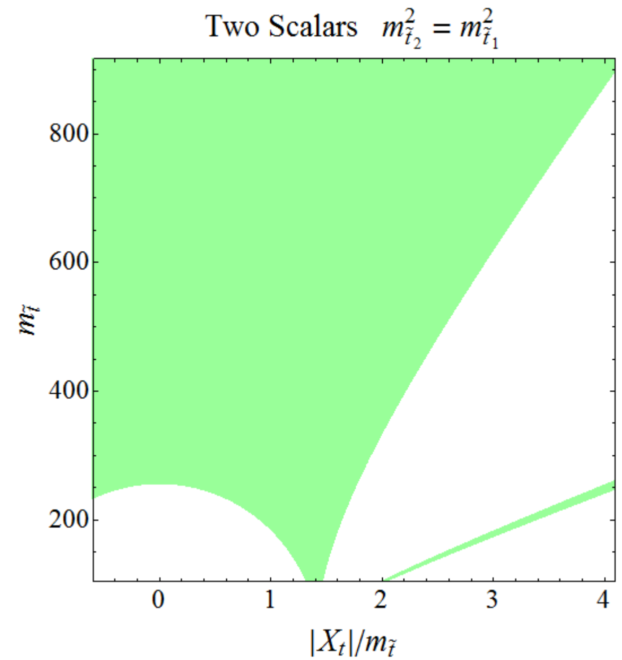
- But with mixing, the signs can change

$$-\mathcal{L}_{stop} = |\tilde{t}|^2\left(\tilde{m}^2 + y^2|H|^2\right) + |\tilde{t}^c|^2\left(\tilde{m}_c^2 + y^2|H|^2\right) + y|H|X_t\left(\tilde{t}\tilde{t}^c + \text{h.c.}\right)$$

$$\frac{c_g}{c_{g,\text{SM}}} = \frac{c_\gamma}{c_{\gamma,\text{SM}}} = 1 + \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

- Intersecting 90% CL. No constraints from the Higgs mass.
- Cancellation of quadratic divergence comes from both stops, so bounds will be weaker.
- Can tune the mixing, to get light stops.

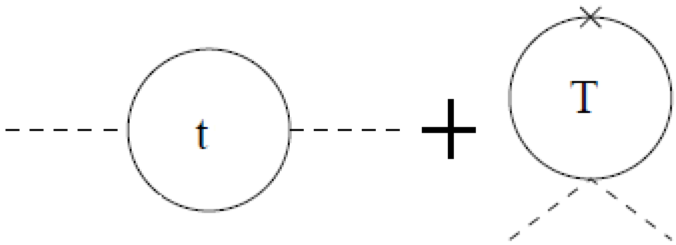




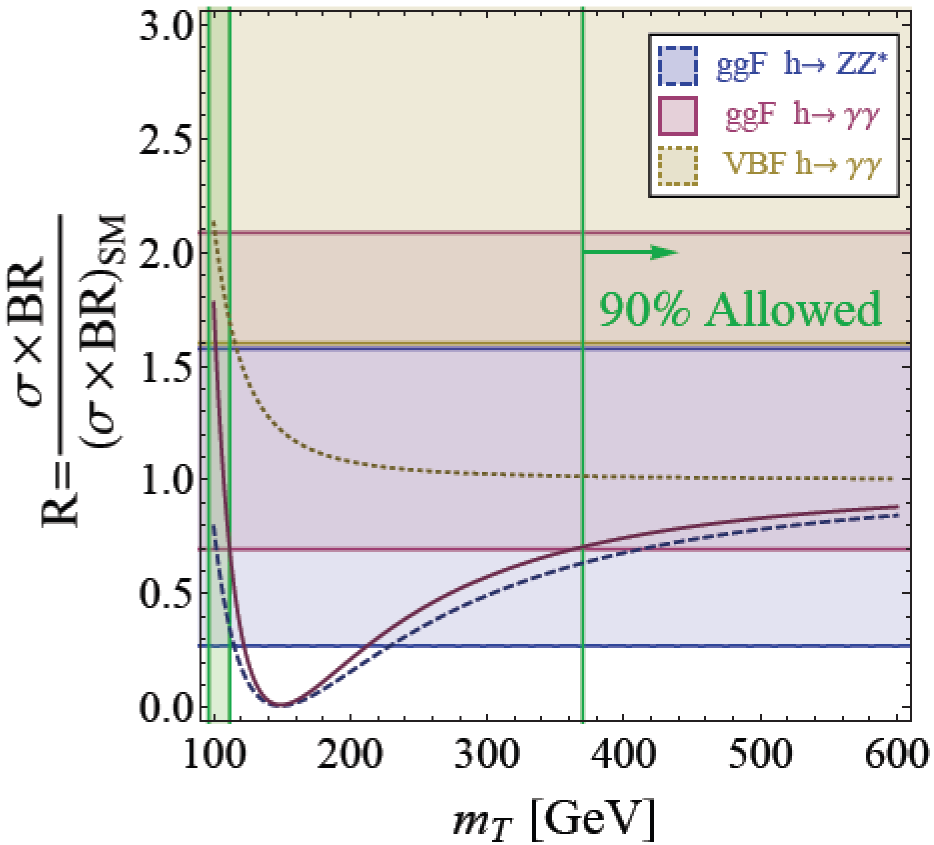
Fermion Partner

- Exactly cancel quadratic divergence:

$$-\mathcal{L} = M_T T\bar{T} - \frac{1}{\Lambda_T} hh^\star T\bar{T} \qquad \frac{1}{\Lambda_T} = \frac{\lambda_t^2}{2M_T}$$



$\Lambda^2 \downarrow \qquad h \to gg \downarrow \qquad h \to \gamma\gamma \uparrow$



Fourth Generation

An aside from Top partner models…

Work in progress, with

Yossi Nir and Tomer Volansky

Fourth Generation

Top’ Bottom’ Tau’ Neutrino’

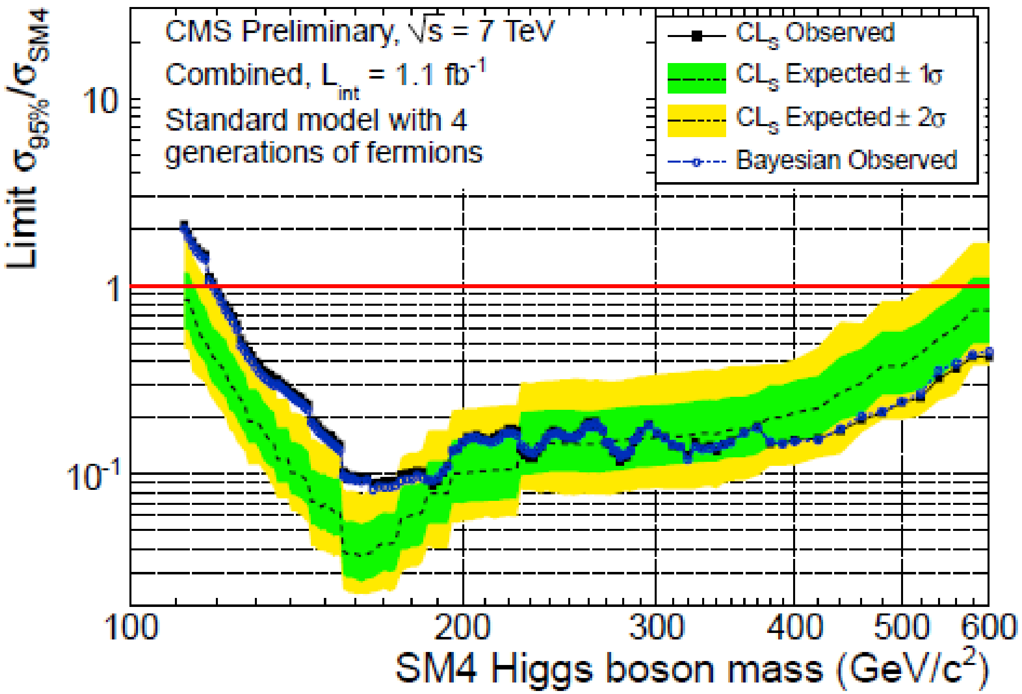
Fourth Generation

$$\Gamma_{h \to gg} \sim |Top + Top' + Bottom'|^2 \sim 9 \times \mathrm{SM}$$

$$\Gamma_{h \to \gamma\gamma} \sim |W - Top - Top' - Bottom' - Tau'|^2 \sim \frac{1}{5} \times \mathrm{SM}$$

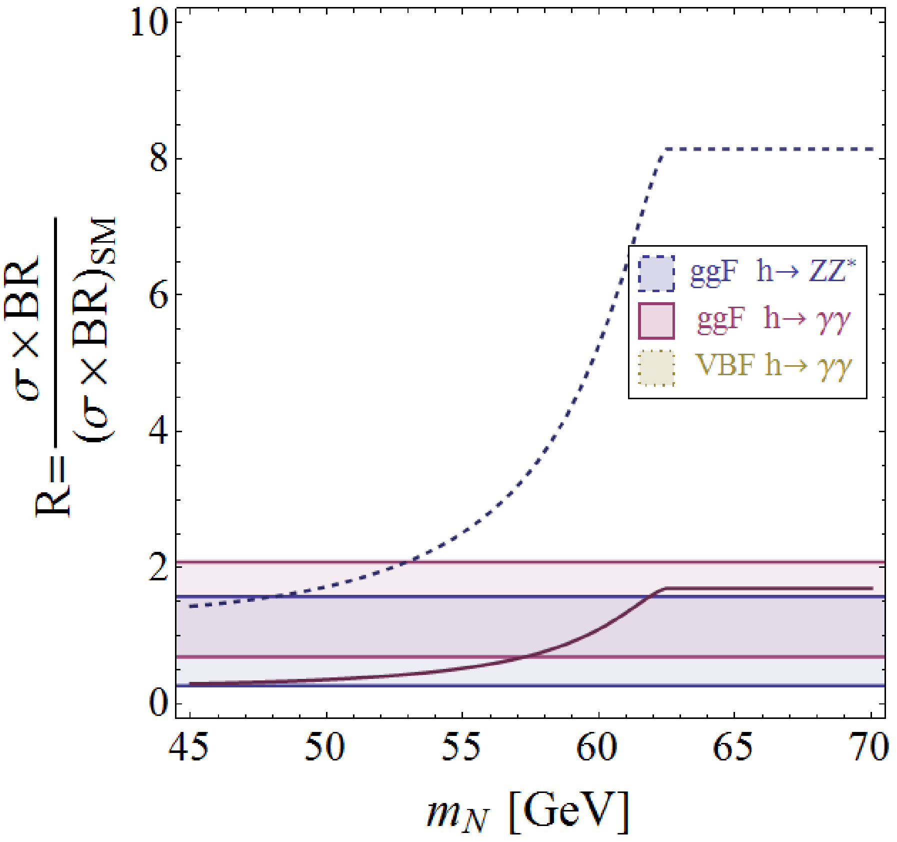
$R_{\gamma\gamma} \sim 1.8$ but $R_{ZZ} \sim 5$

Fourth generation
Is ruled out!



Fourth Generation – Leading Order

- Not the entire story: There is a heavy neutrino, and the Higgs can decay mostly invisibly.



SM4 + 2HDM
Chen, He 1202.3072

Fourth Generation Saved!

Fourth Generation – Higher Order

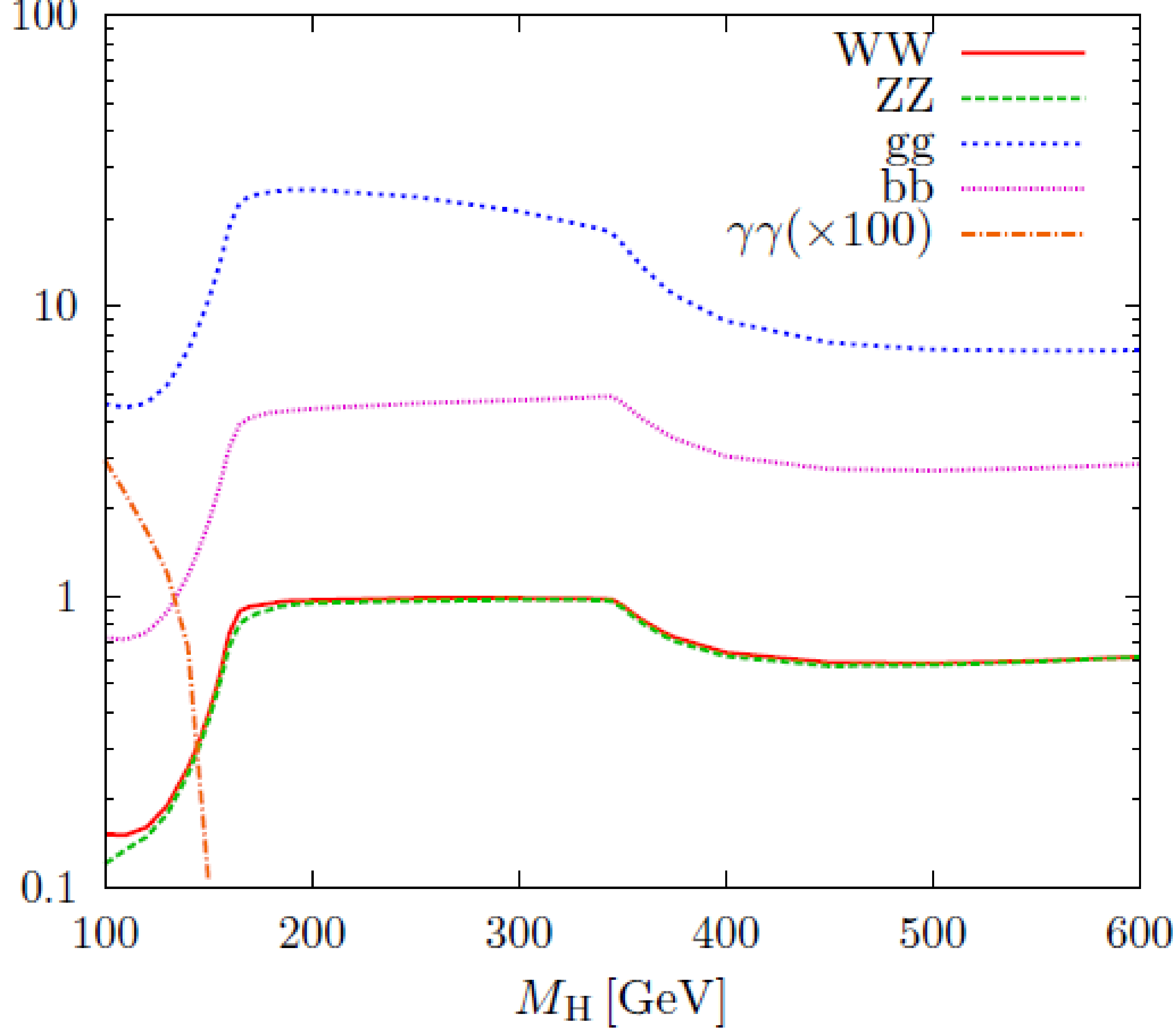
- Not the entire story:

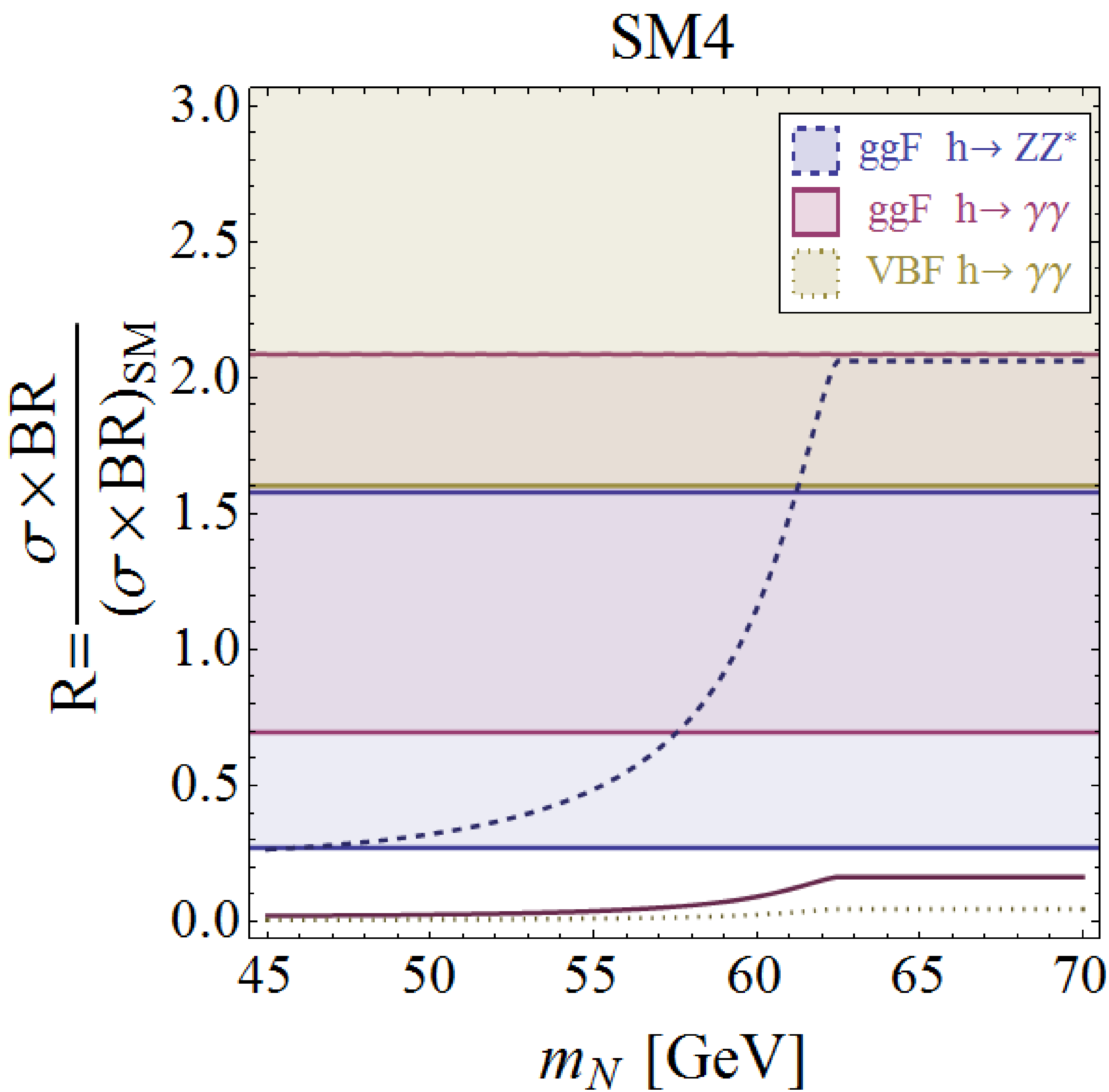
Large Yukawa couplings means large corrections

Two loop diagrams lead to an even larger cancellation between the W-loop and fermion-loops

$$\Gamma_{h\to\gamma\gamma} \sim |W - Top - Top' - Bottom' - Tau' - 2\ \mathrm{Loop}|^2$$

Denner, Dittmaier, Muck, Passarino, Spira, Sturm, Uccirato, Webber, 1111.6395





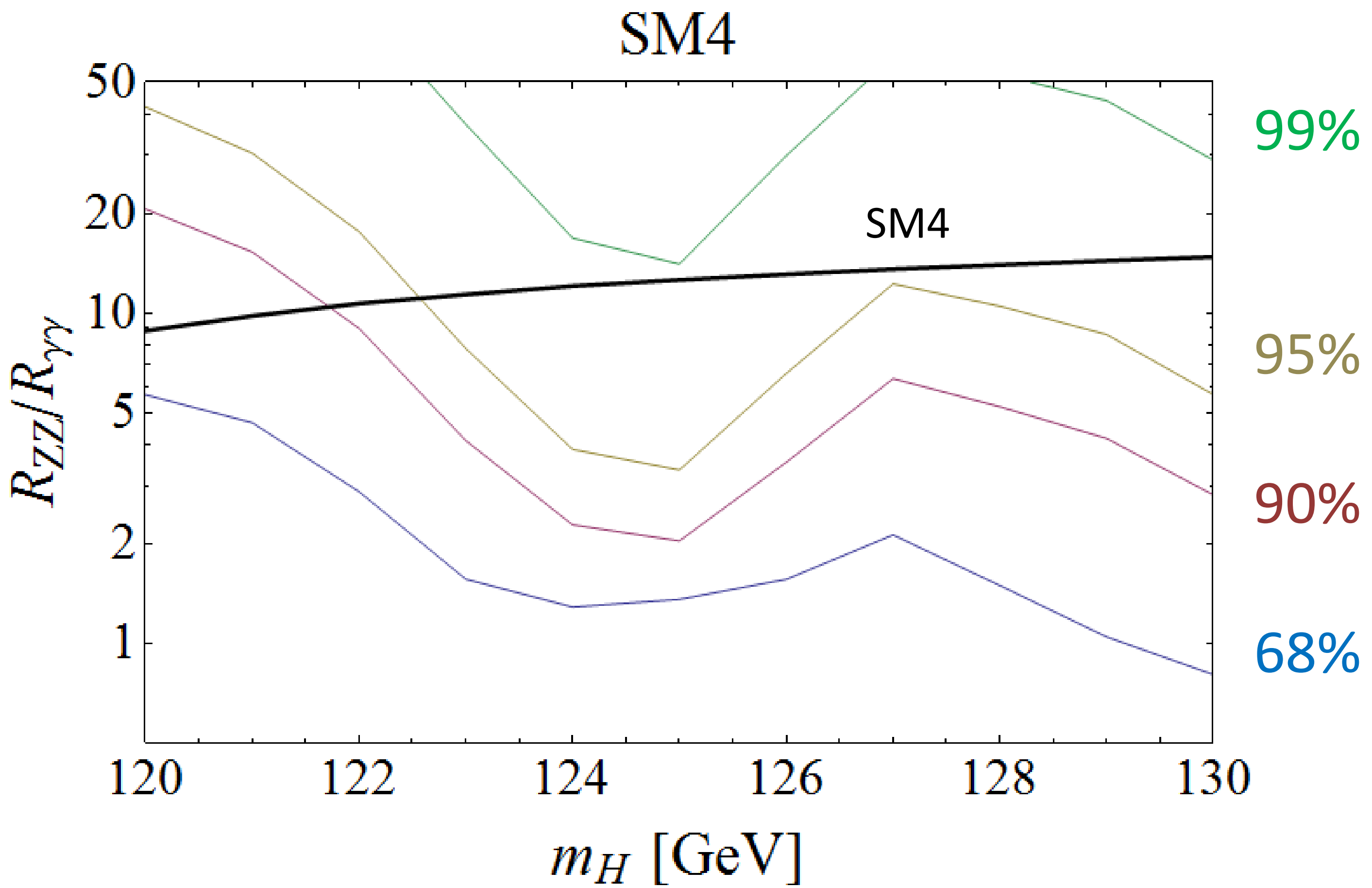
SM4
ggF h→ ZZ*
ggF h→ γγ
VBF h→ γγ
R=(σ×BR)/(σ×BR)SM
3.0
2.5
2.0
1.5
1.0
0.5
0.0
45
50
55
60
65
70
mN [GeV]

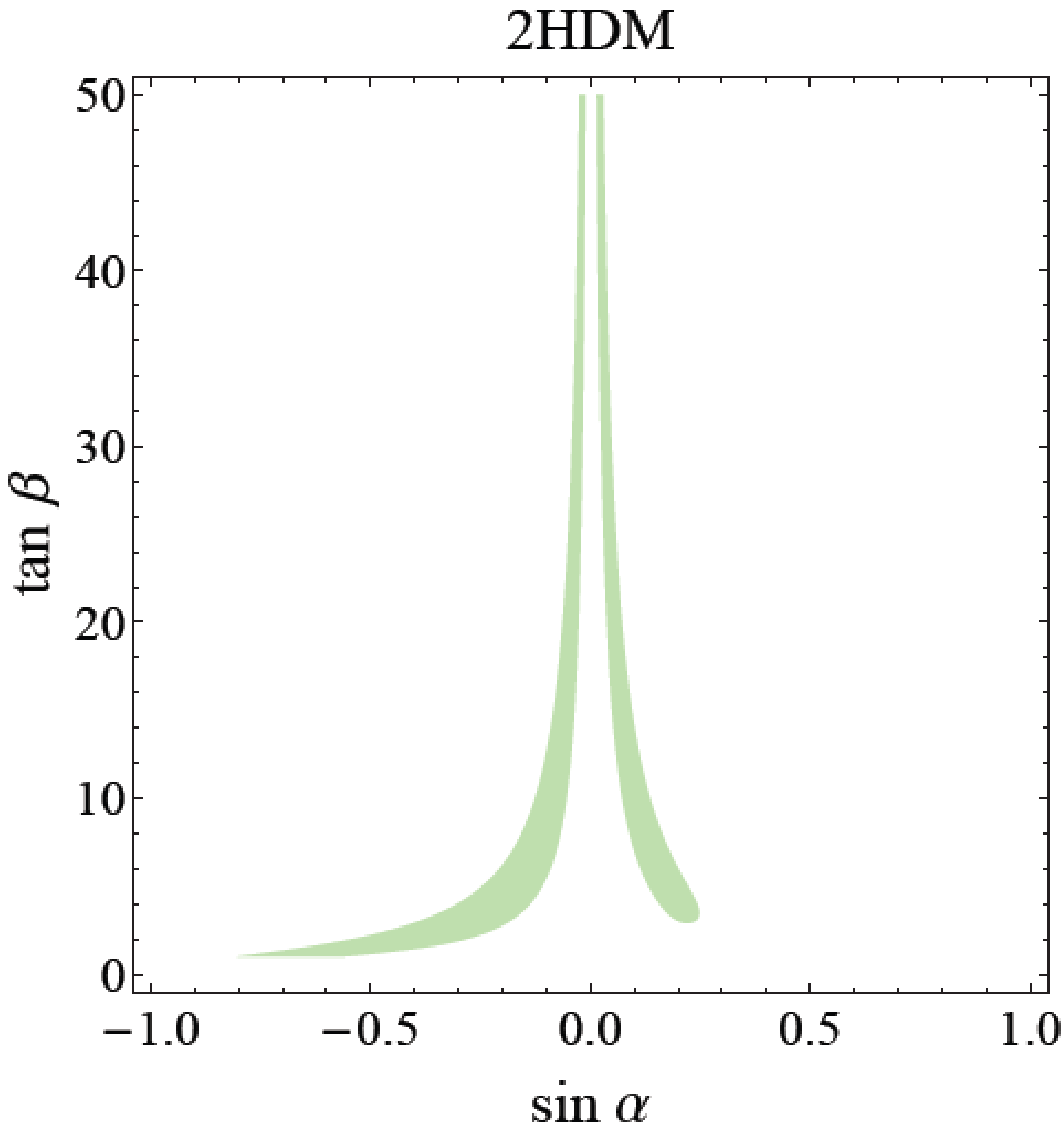
- Consider

$$R_{ZZ}/R_{\gamma\gamma} = (\Gamma_{h\to ZZ^*}/\Gamma_{h\to\gamma\gamma})/(\Gamma_{h\to ZZ^*}/\Gamma_{h\to\gamma\gamma})|_{SM}$$

Does not depend on any other widths:

Independent of the cross section and invisible width



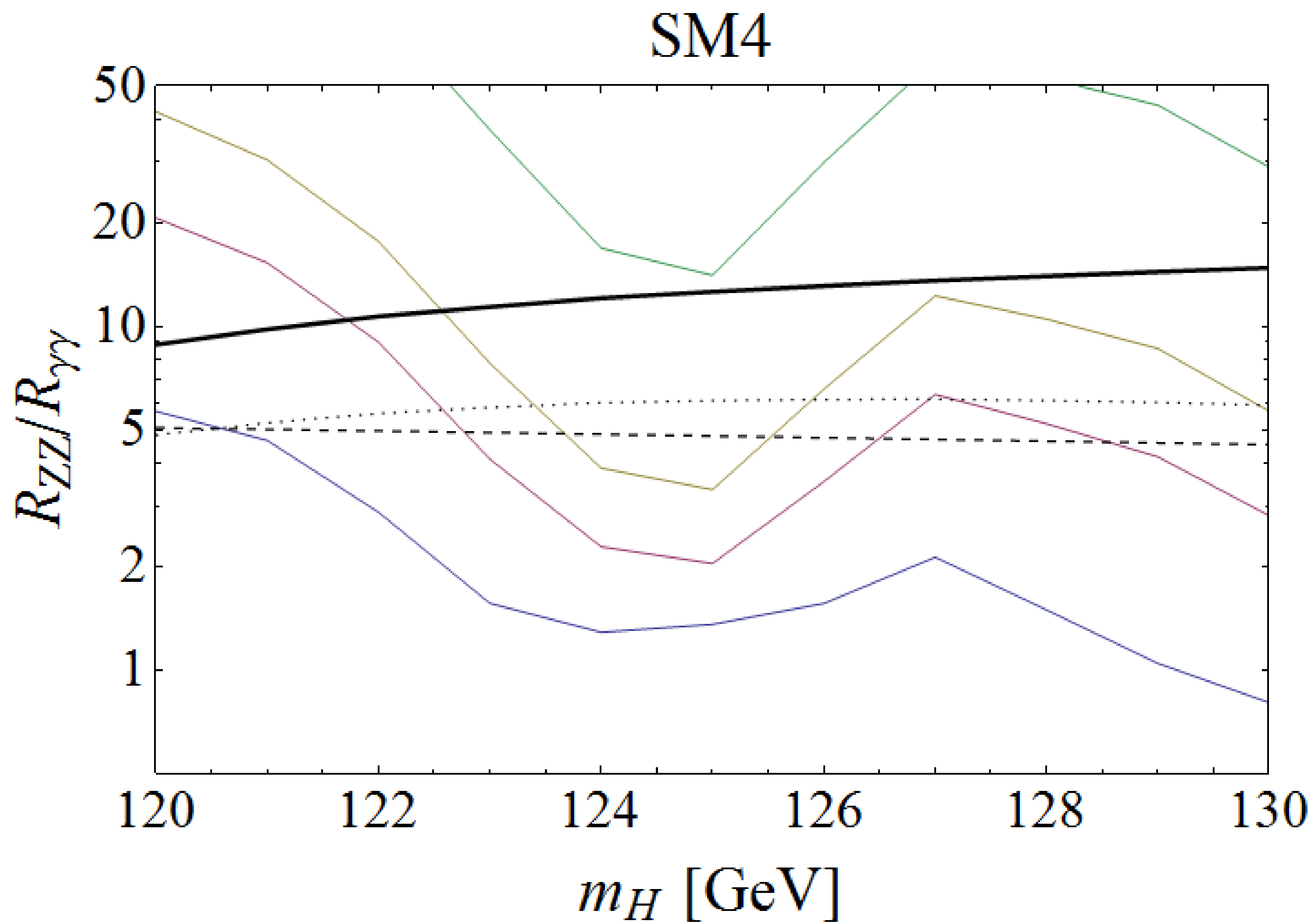


Ferreira, Santos, Sher, Silva, 1112.3277
Ferreira, Santos, Sher, Silva, 1201.0019
Cerver, Gerard, 1202.1973
Blum, D'Agnolo, 1202.2364

Summary

- Finally, a new particle might have maybe possibly been seen.
- Higgs measurements are close to SM-like
  - Little Hierarchy Problem
- New physics can be seen in Higgs production and decay
  - Related to Naturalness
- Precision Higgs can be begin

The End.


SM4
50
20
10
5
2
1
$R_{ZZ}/R_{\gamma\gamma}$
120
122
124
126
128
130
m_H [GeV]