Making Sense of a 125 GeV Higgs Boson

March 2012

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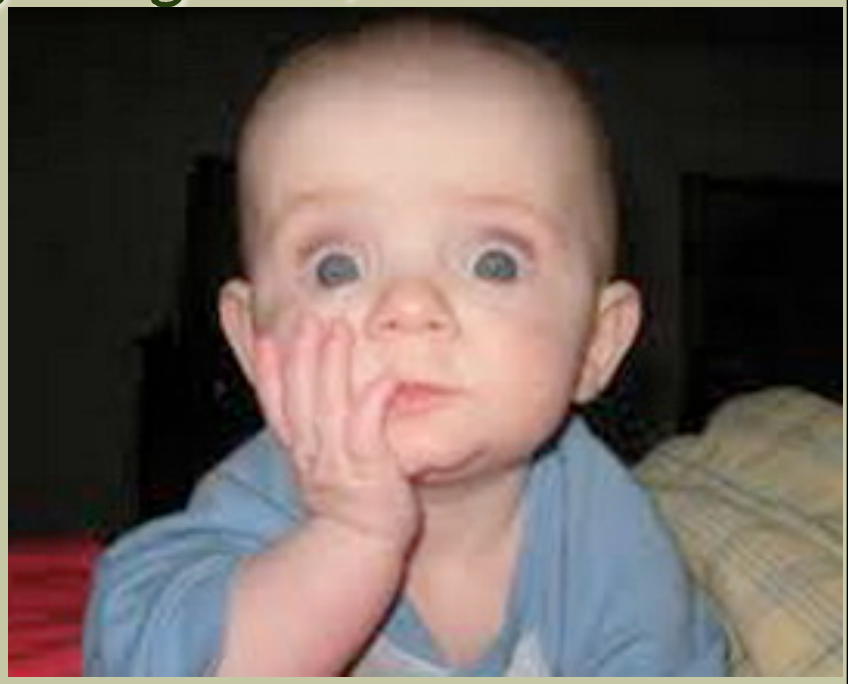
Based on:

D. Carmi, A. Falkowski, E. Kuflik, TV [arXiv: 1202.3144 + work in progress]
E. Kuflik, Y. Nir, TV [to appear soon]

Where is my new physics??

(Is the damn SM right again?)

At the moment, Higgs searches focus (mostly) on the SM Higgs

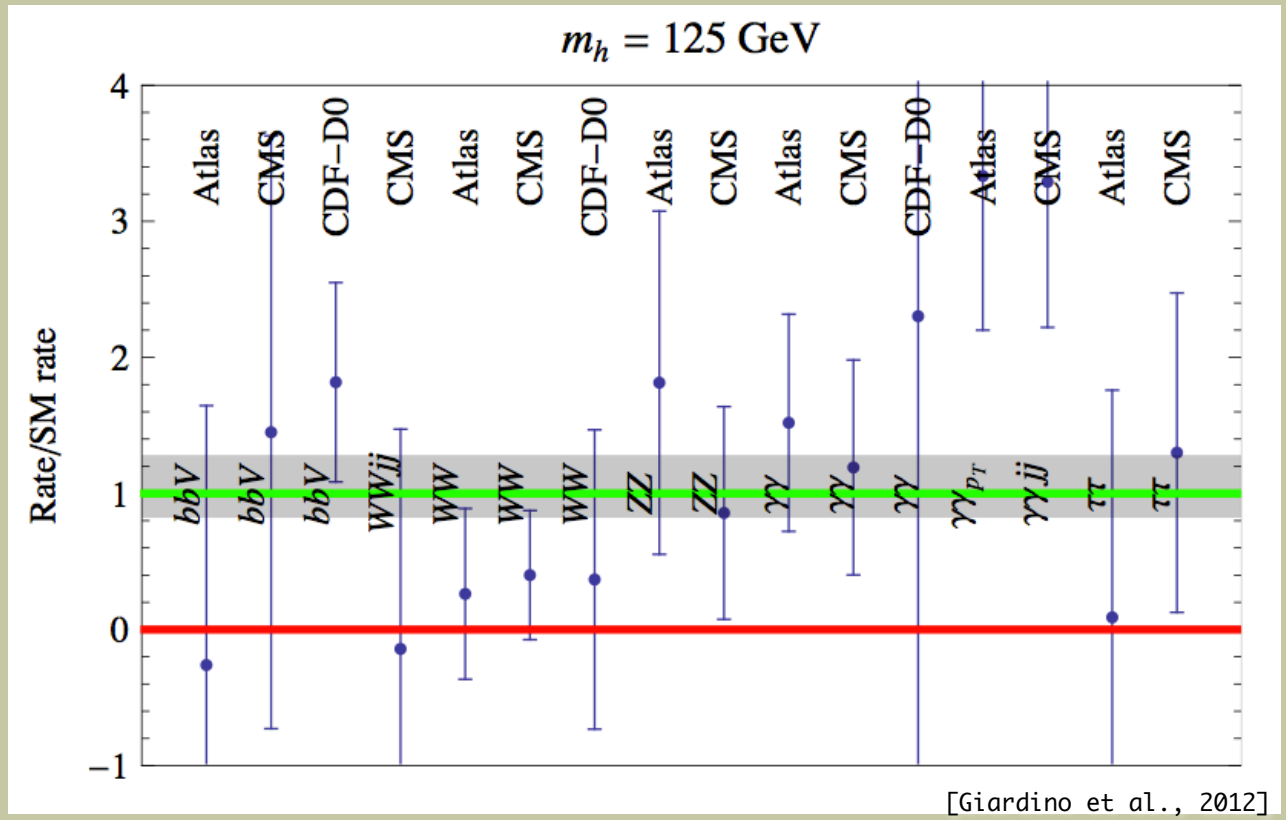


But what do they imply for NP?

Given the signal, how sure are we that it's a SM Higgs?

What do we really measure?

- Experiments provide the results of many different channels.
- Once a signal is observed the best fit signal-strength = (rate / SM rate) is quoted.
- But in many cases the searches are inclusive and the SM production modes are assumed.



What do we really want?

- It would certainly be great (as was argued in the last talk by Jamison Galloway) if experimentalists provide us with the likelihood functions for each search (or enough information to reconstruct them..).
- However, we can settle for much less:
  - Each experiment and for each search, the efficiencies for the different production modes exist.
  - It is therefore possible for the experiments to **fit** for signal-strength in each channel and production mode:

	$\gamma\gamma$	ZZ	WW	bb	...
ggF	1.6±0.7	2.1±1.5	...		
VBF	3.6±1.7	...			
WH	...				
ZH					

What do we really want?

- Such a table is great, but even more can be done (quite trivially).
- All the different channels are controlled in a non-trivial and correlated way, by the couplings of the Higgs to SM particles.
- New physics models simply **change** the various Higgs couplings and therefore **rescale** the different channels in a model-dependent way.

A very useful way to present the data is therefore to provide the allowed region in the multi-dimension space of Higgs couplings.

The Effective Higgs Action

- We define the effective action at $\mu = m_h = 125$ GeV.
- We then write the most general Lagrangian (relevant for LHC):

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

- top is already integrated out.
- (Note - This is more general than the action that shows up in composite Higgs models).
- hWW and hZZ have the same coupling (follows from custodial symmetry).
- In the SM:

$$c_V = c_b = c_\tau = 1 \qquad c_g \simeq 1 \qquad c_\gamma \simeq 2/9$$

The Effective Higgs Action

- Relation to rates is straightforward (at LO):

$$\frac{\Gamma(h \to WW^*)}{\Gamma_{SM}(h \to WW^*)} = \frac{\Gamma(h \to ZZ^*)}{\Gamma_{SM}(h \to ZZ^*)} \simeq |c_V|^2$$

$$\frac{\Gamma(h \to b\bar{b})}{\Gamma_{SM}(h \to b\bar{b})} \simeq |c_b|^2$$

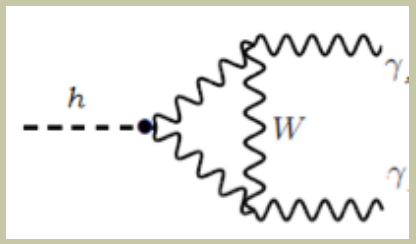
$$\frac{\Gamma(h \to gg)}{\Gamma_{SM}(h \to gg)} \simeq |c_g|^2$$

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

- For m_h=125 GeV,

$$\hat{c}_\gamma \simeq c_\gamma - c_V$$

$$\hat{c}_{\gamma,\mathrm{SM}} \simeq -0.81$$



and the total width:

$$\frac{\Gamma(h)}{\Gamma_{\mathrm{SM}}(h)} \simeq 0.65 c_b{}^2 + 0.25 c_V{}^2 + 0.1 c_g{}^2$$

The Effective Higgs Action

- Consequently, there is a clear mapping from the effective action to the various channels.
- Assuming for simplicity, h→bb dominates width (fits below use exact relations..):

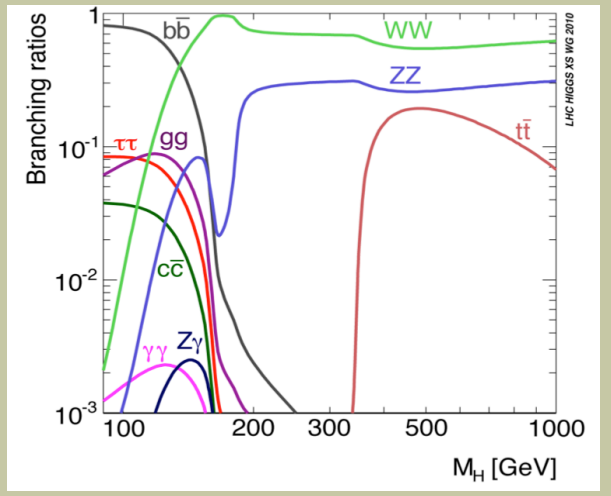
$$
\begin{aligned}
R_V &\equiv \frac{\sigma(pp\to h)\mathrm{Br}(h\to ZZ^*)}{\sigma_{SM}(pp\to h)\mathrm{Br}_{SM}(h\to ZZ^*)} \simeq \left|\frac{c_g c_V}{c_b}\right|^2 \\
R_\gamma &\equiv \frac{\sigma(pp\to h)\mathrm{Br}(h\to \gamma\gamma)}{\sigma_{SM}(pp\to h)\mathrm{Br}_{SM}(h\to \gamma\gamma)} \simeq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

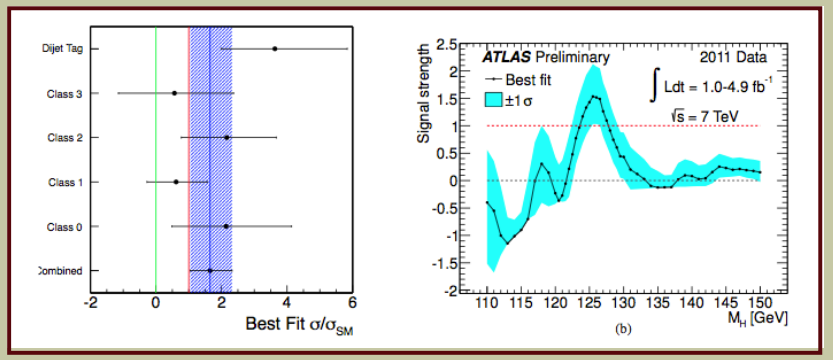
The (many) different channels are correlated and depend on the few parameters of the effective action. A fit to these parameters can therefore provide strong bounds!

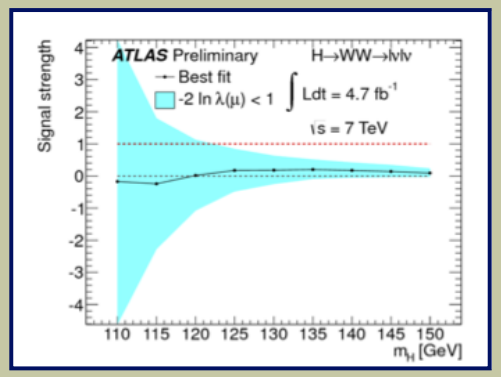
Some Results:
Constraining the Effective Action with a 125 GeV Higgs

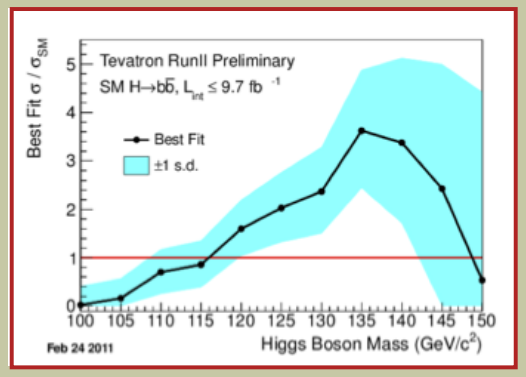
Data

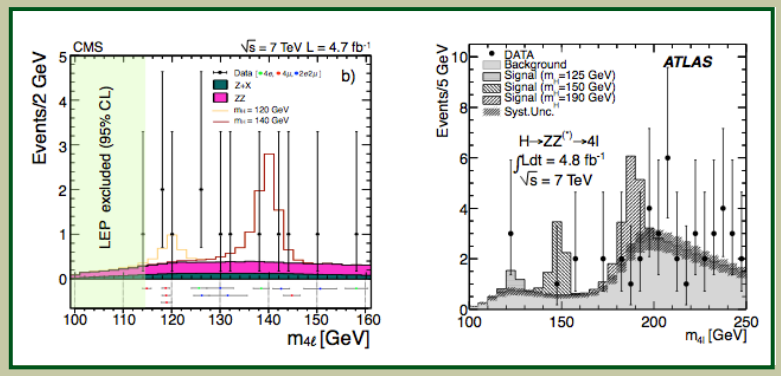
- So what statements can we make about the Higgs?
- 125 GeV is a lucky mass - we can probe all channels (probably to verify, once again, that the SM is correct...).
- To demonstrate, we use 5 channels:
  [see also Azatov et al.; Espinosa at al; Giardino et al.]
  - h→γγ (ggF and VBF, CMS + ATLAS)
  - h→ZZ*→4l (CMS + ATLAS)
  - h→bb (Tevatron)
  - h→WW* (ATLAS)



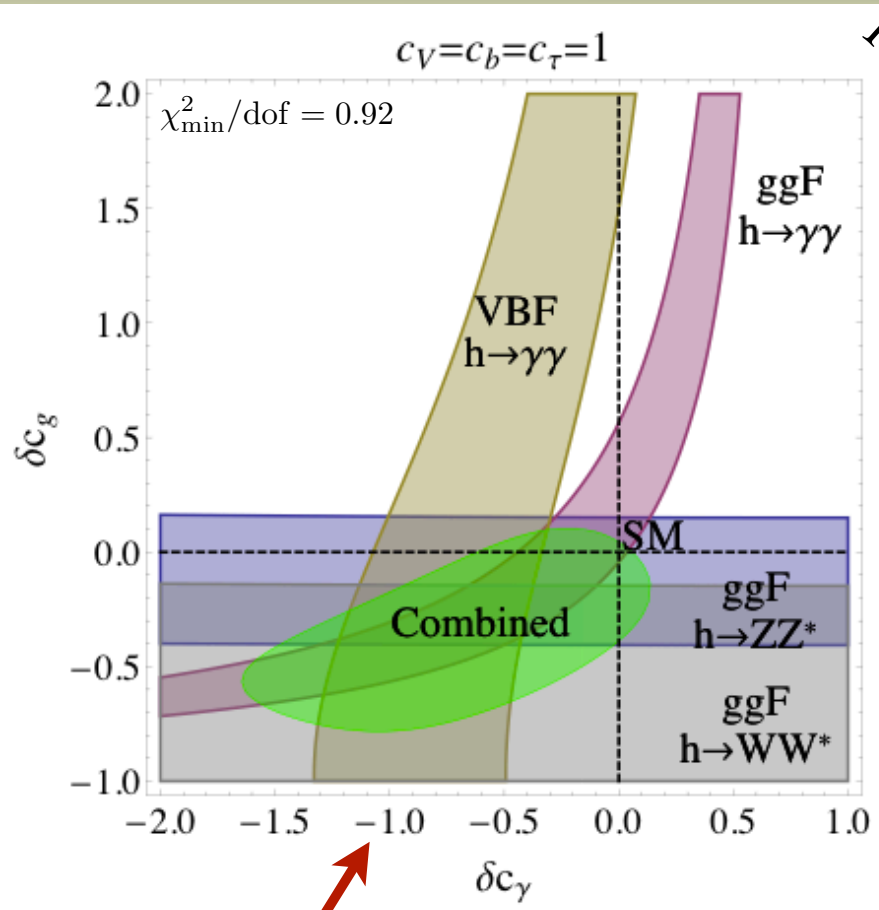




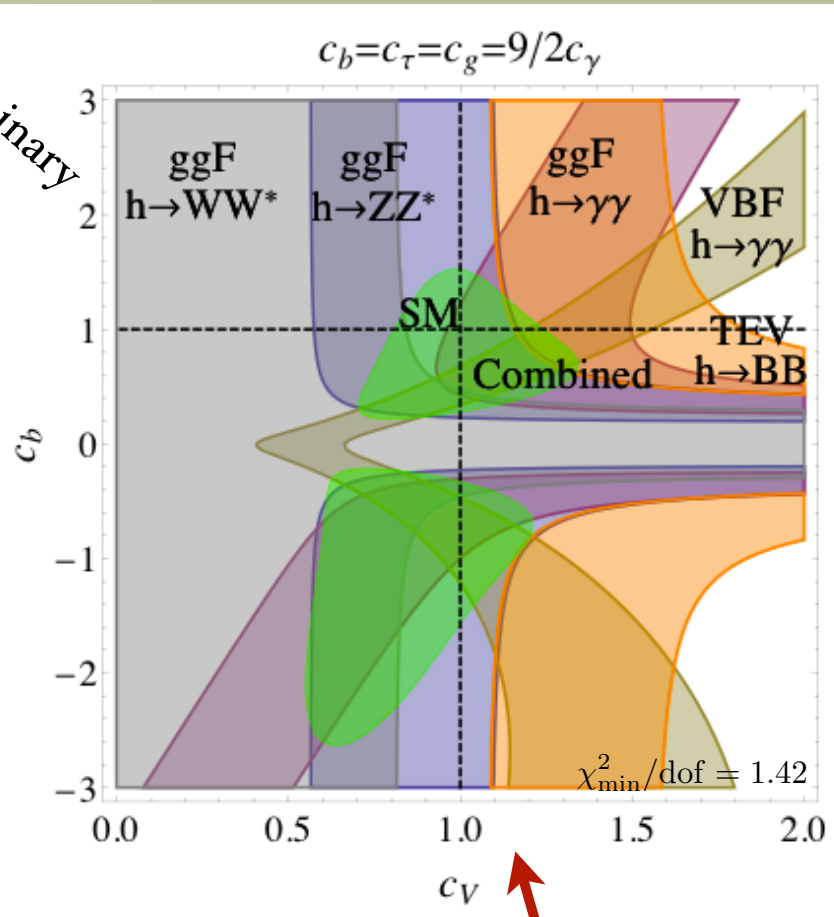




Fits - The Plots We Want..



Preliminary



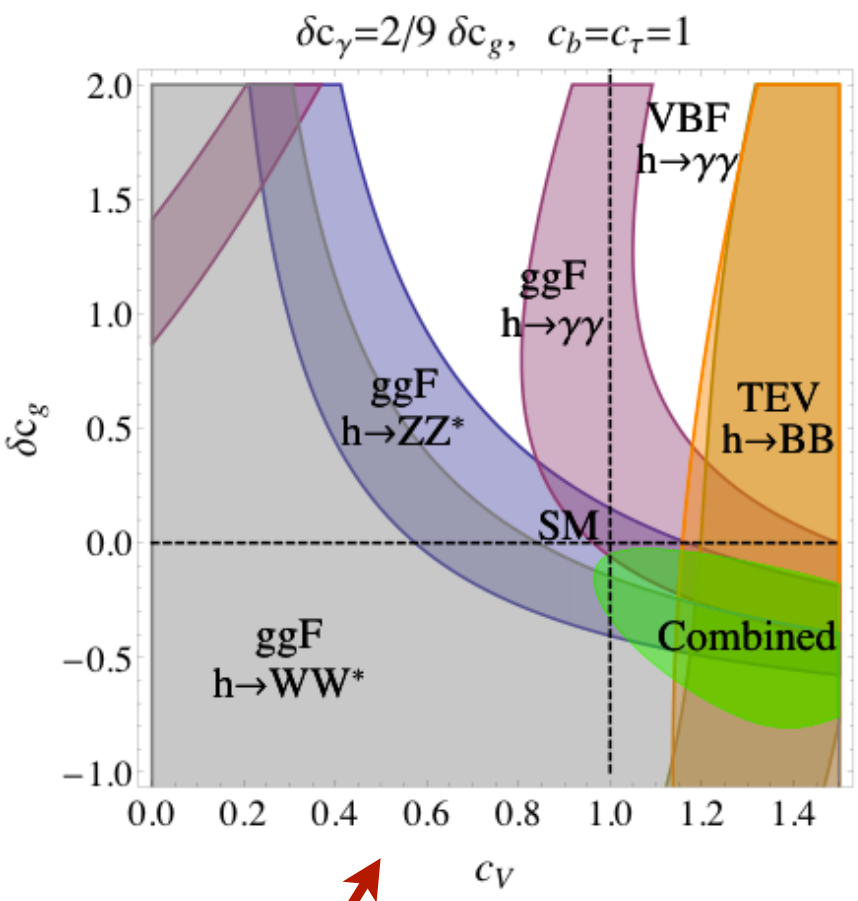
Relevant to models affecting only dimension-5

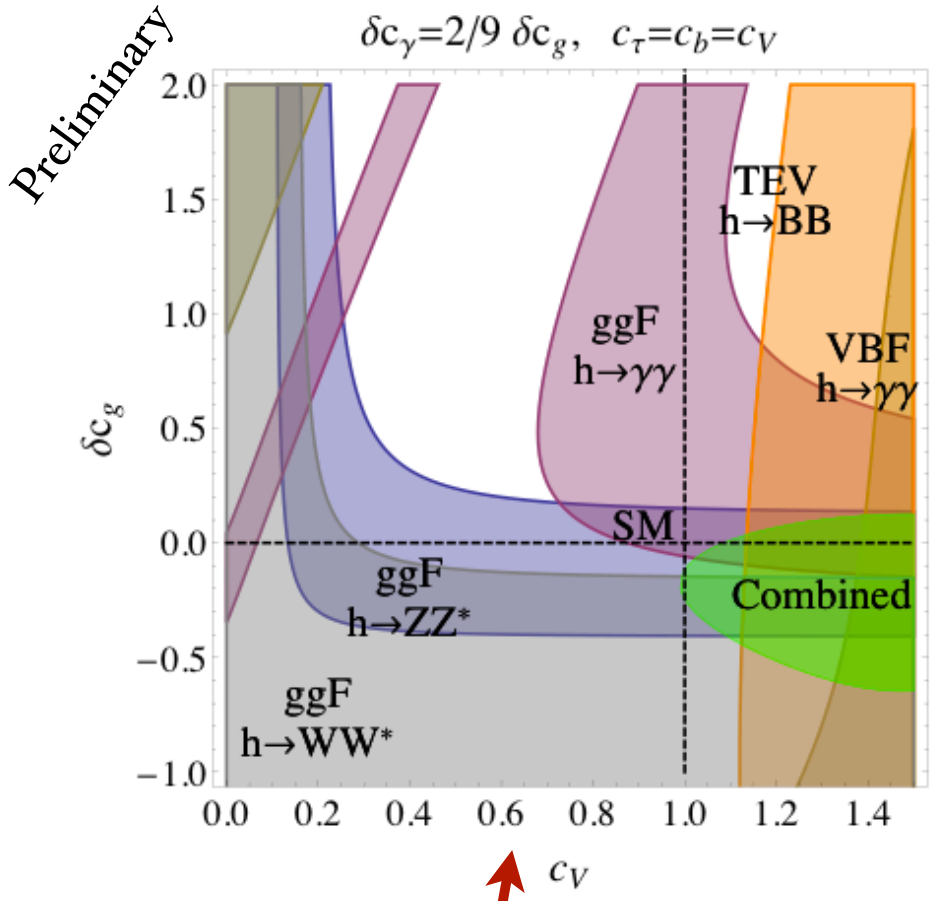
Tevatron bound never within 1σ

Composite Higgs inspired parametrization

Relation: $c_g=9c_\gamma/2$ occurs for top partners.

Fits - The Plots We Want..





Only c_V and dimension-5 allow to vary

All couplings may vary

Occurs for non-universal couplings (e.g. Twin Higgs)

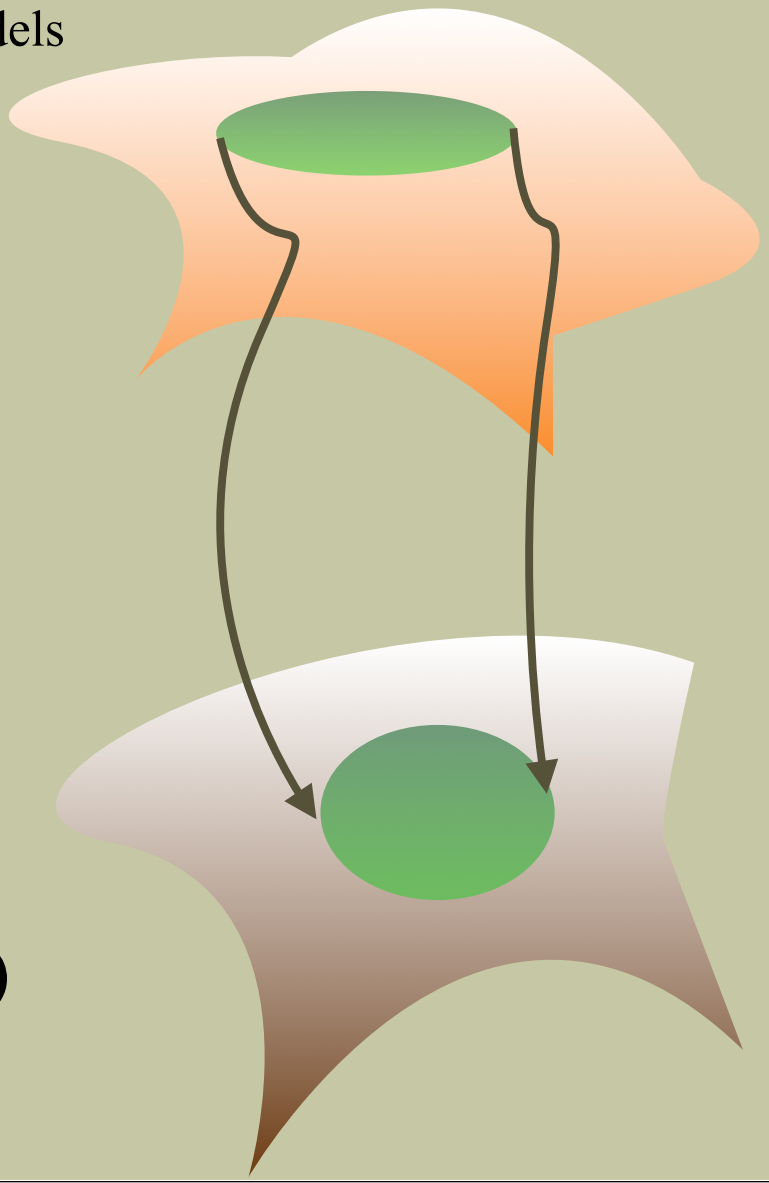
What Do We Learn?

- First, the SM feels some tension (of course 2-sigma anomalies in the SM come and go..).
- More importantly, we can now constrain NP models

$\mu=\Lambda$ $\quad \mathscr{L} = \mathscr{L}(g_1,..,g_k;\, h)$

RGE

$\mu=m_h$ $\quad \mathscr{L} = \mathscr{L}(c_b,c_V,c_\gamma,c_{g,..};\, h)$

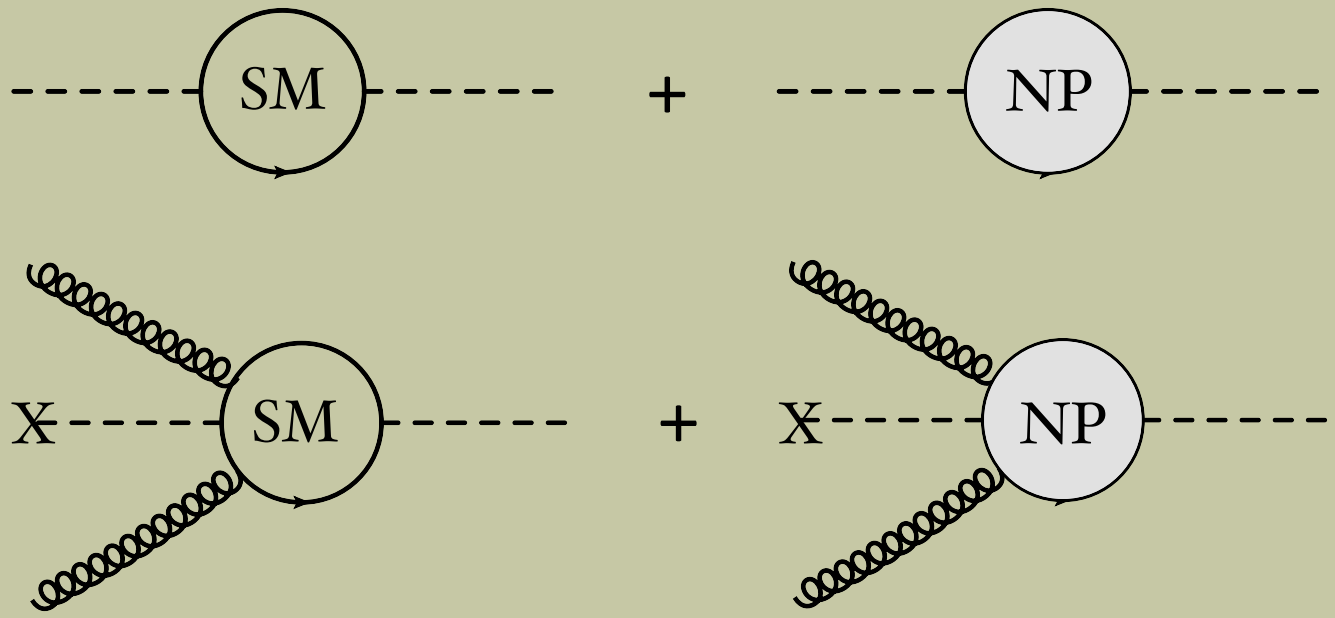


Example:
Naturalness and the Higgs

Effects of New Physics

The Higgs is an excellent probe of new physics in general and of the fine tuning problem in particular.

- New particles introduced in models that resolve the fine tuning, also enter in the gluon fusion and diphoton rates.



$$\Gamma(h \to \gamma\gamma) = |\mathrm{W} - \mathrm{top} \mp \mathrm{NP}|^2$$

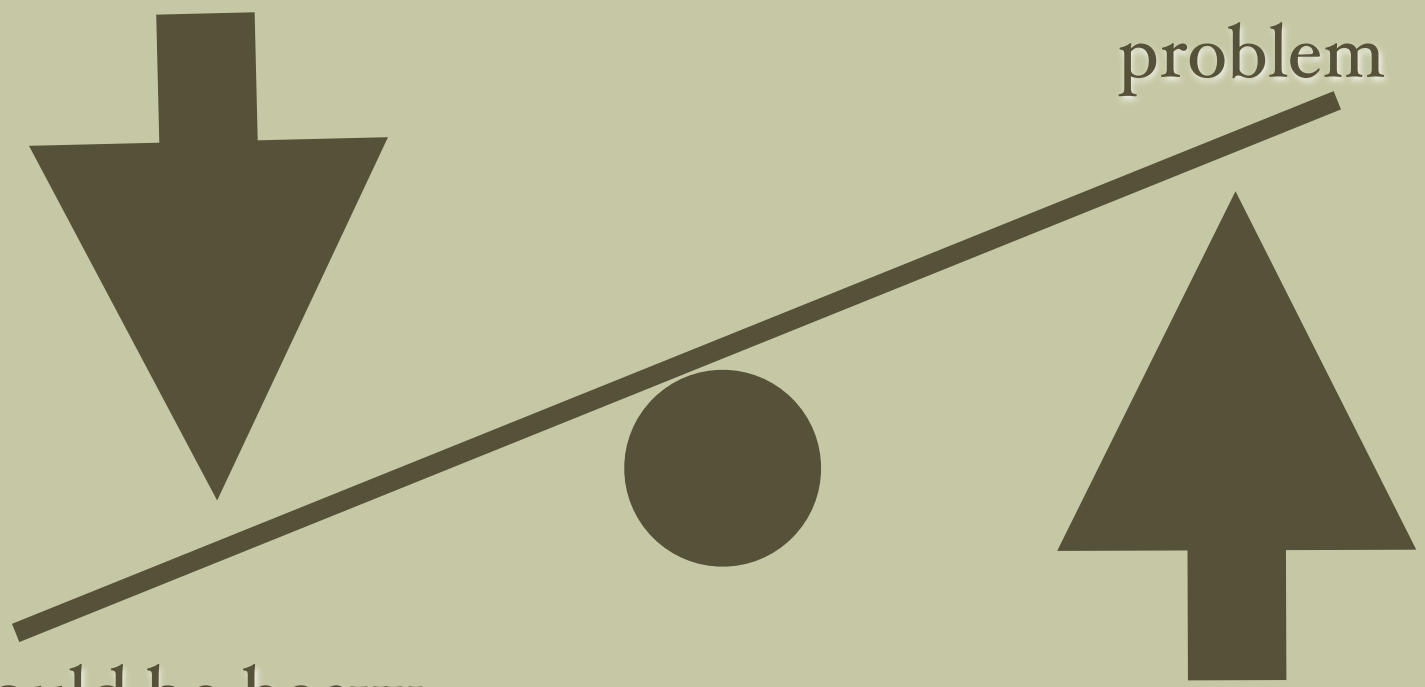
Dominates over top contribution

In may cases lowers rate

$$\Gamma(h \to gg) = |\mathrm{top} \pm \mathrm{NP}|^2$$

The New Little Hierarchy Problem?

NP Should be light
to minimize hierarchy
problem



NP Should be heavy
to decouple from SM
rates

Single Scalar Top Partners

- As a first example consider a toy model: scalar top partner (same EM charge and color).

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

- In order to cancel quadratic divergence: $\lambda = 2y^2$

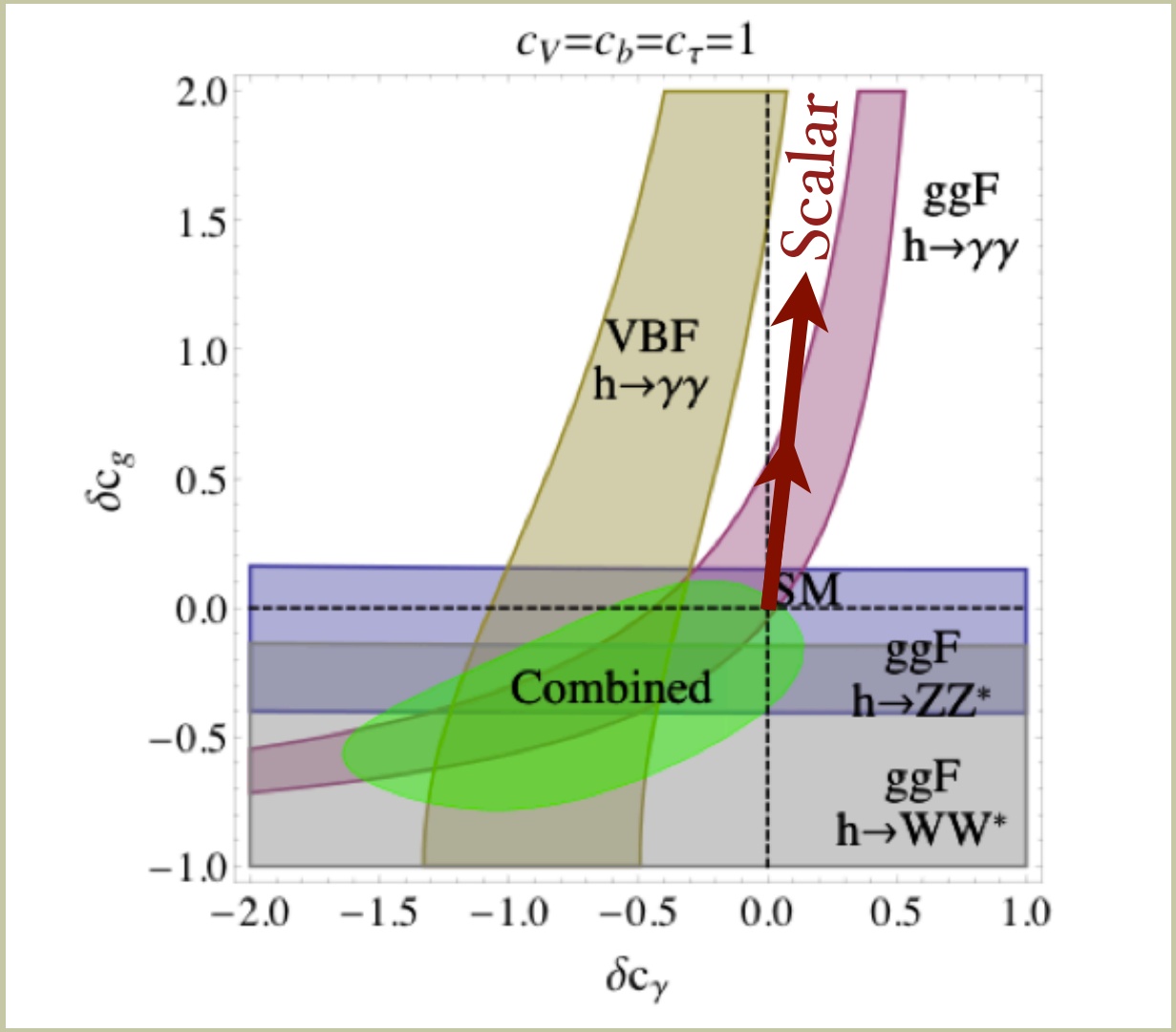
- For $m_{\tilde{t}} \gg m_h/2$

$$\frac{c_g}{c_{g,\text{SM}}} = \frac{c_\gamma}{c_{\gamma,\text{SM}}} \simeq 1 + \lambda\frac{v^2}{8m_{\tilde{t}}^2} = 1 + \frac{m_t^2}{2m_{\tilde{t}}^2}\,, \qquad c_V = c_b = 1$$

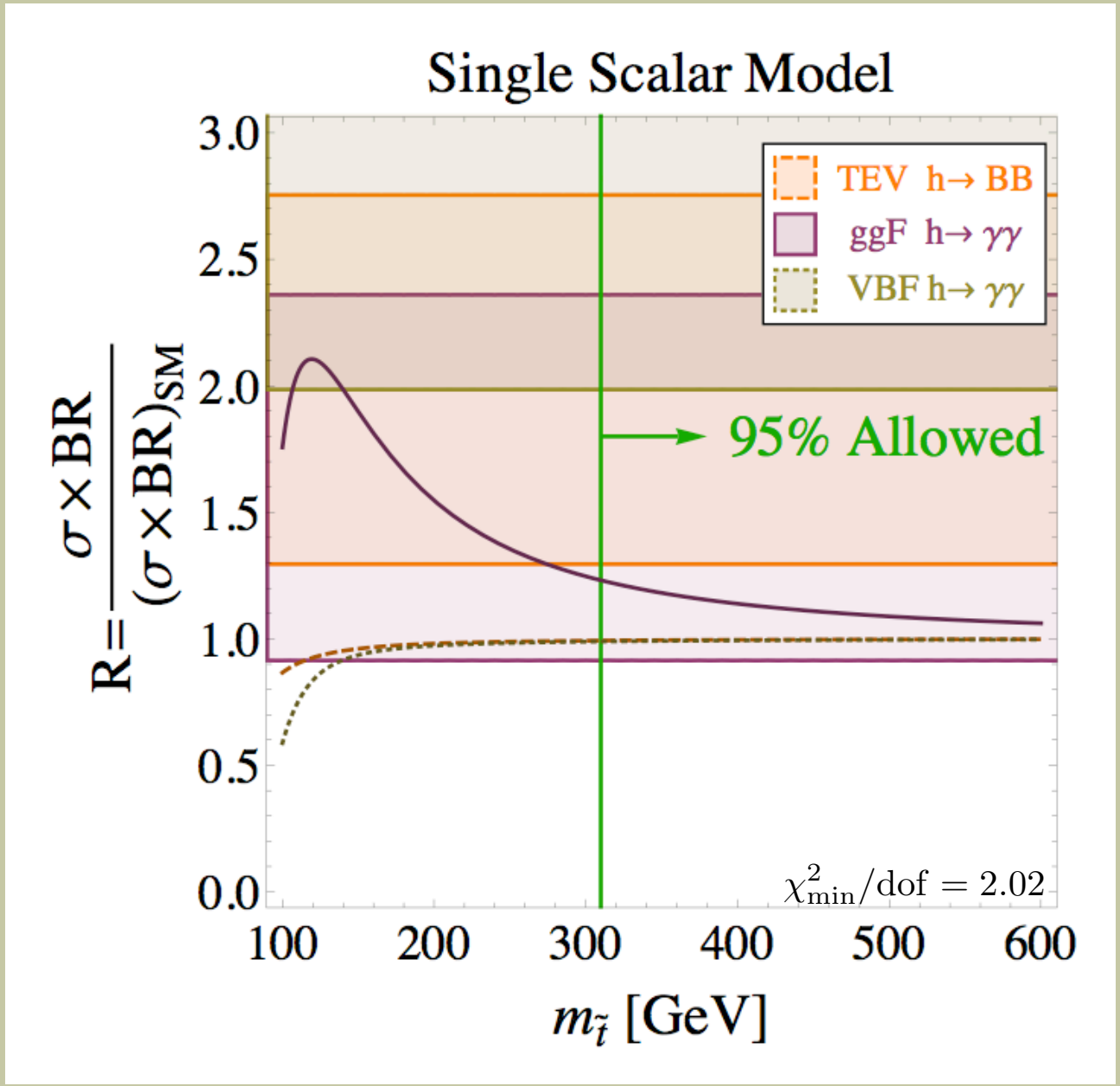
- So top partner contributes same as top (depends on a single parameter) which implies:

$$h \to gg \uparrow \qquad h \to \gamma\gamma \downarrow$$

Single Scalar Top Partners



Single Scalar Top Partners



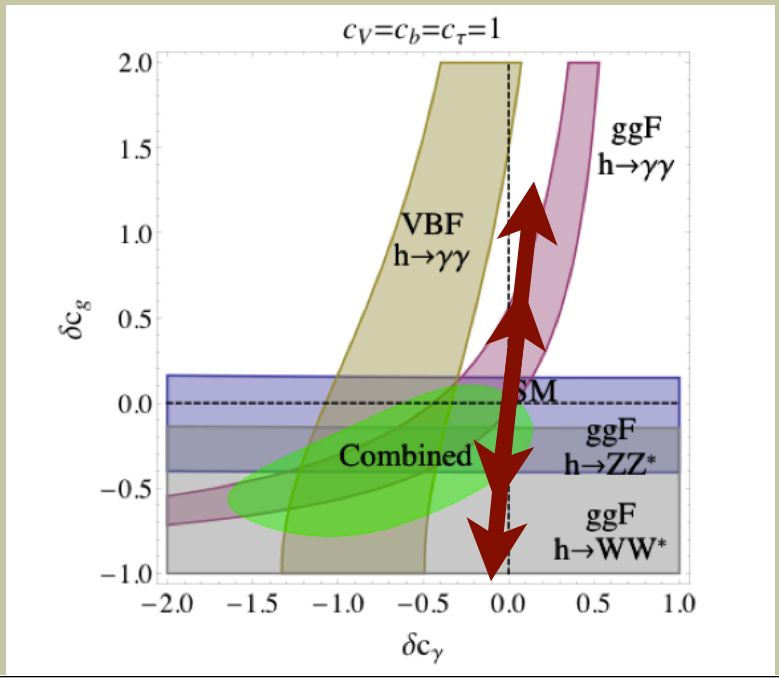
Two Scalar Top Partners (MSSM-like)

- Two scalar tops can mix, changing their coupling to the Higgs.
- The general Lagrangian:

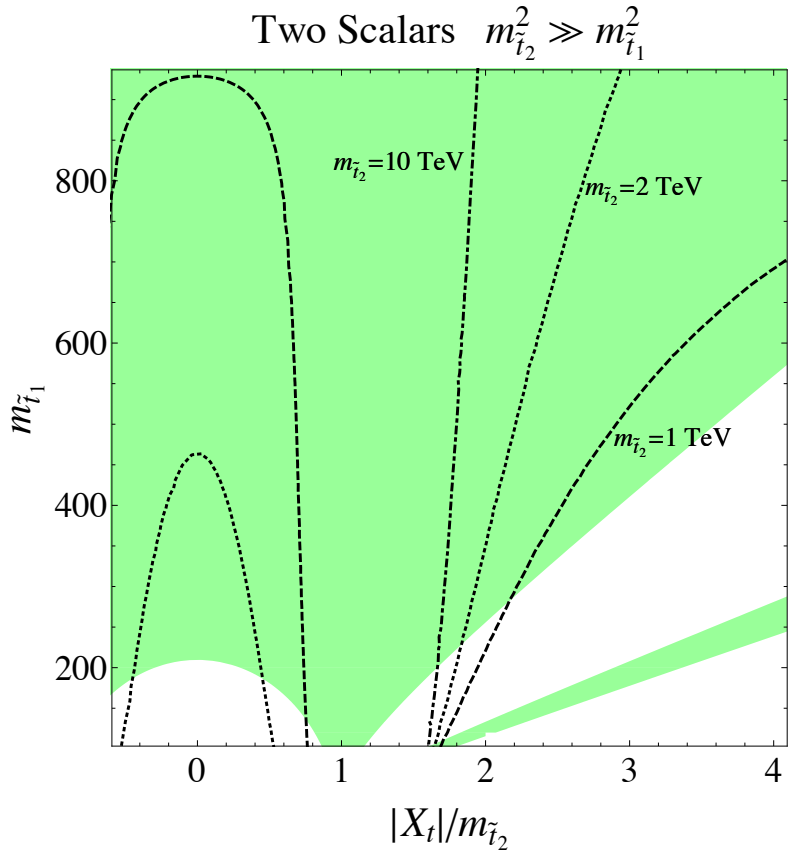
$$-\mathcal{L}_{stop} = |\tilde{t}|^2 \left(\tilde{m}^2 + y^2|H|^2\right) + |\tilde{t}^c|^2 \left(\tilde{m}_c^2 + y^2|H|^2\right) + y|H|X_t \left(\tilde{t}\tilde{t}^c + \text{h.c.}\right),$$

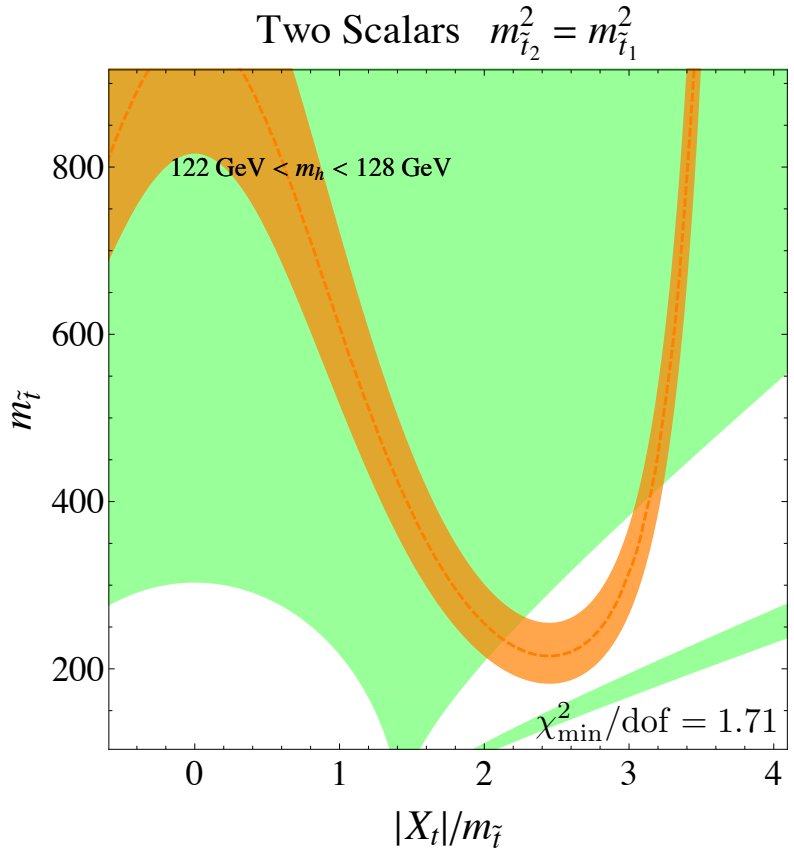
- This is the same as MSSM in the decoupling limit, with $X_t = |A_t - \mu \cot\beta|$
- The effect of mixing is to allow negative contributions to h→gg and h→γγ:

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



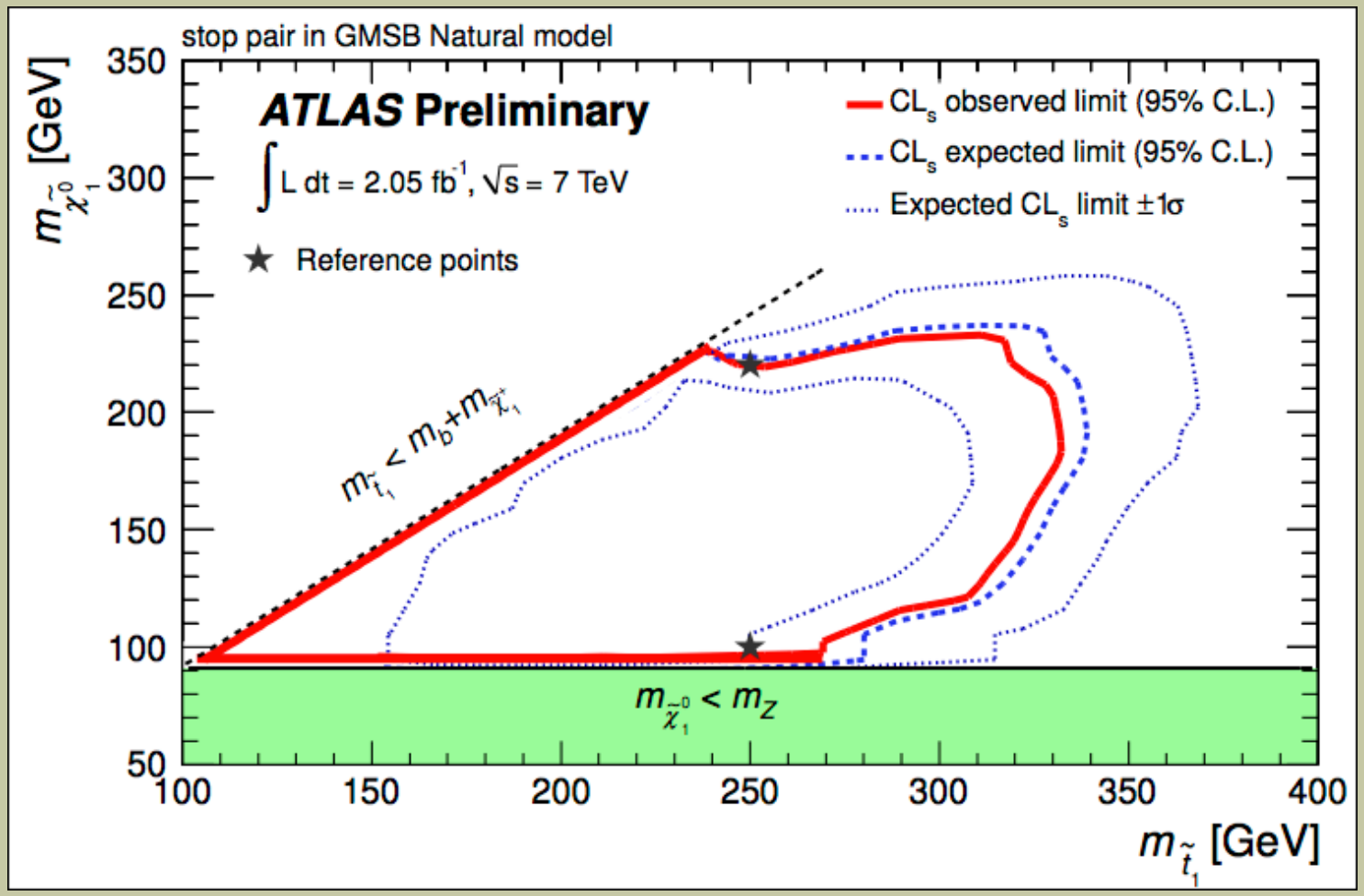
Two Scalar Top Partners (MSSM-like)





- Without tuning the mixing, stops must be heavier than ≳200 GeV.
- Without additional contributions to the Higgs mass, stops should be even heavier.

Two Scalar Top Partners (MSSM-like)



- The "model independent" result obtained, is not far from the current model-dependent direct stop searches.

Fermionic Top Partner

- A similar analysis can be done with a fermionic top partner.
- To cancel the top-loop, interactions must include non-renormalizable terms.

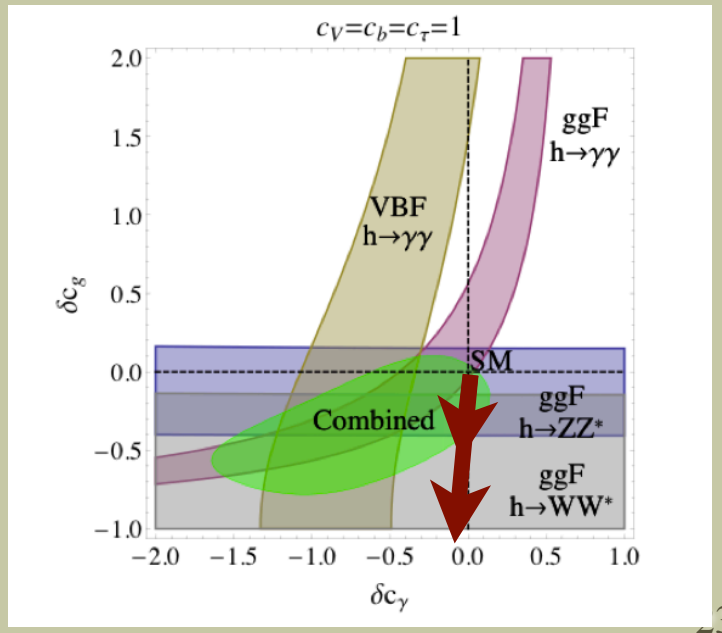
$$-\mathcal{L}_{top} = y_1(|H|^2)HQt^c + y_2(|H|^2)HQT^c + M_1(|H|^2)Tt^c + M_2(|H|^2)TT^c + \text{h.c.}$$

- In the case of no mixing ($y_2 = M_1 = 0$) as in Little Higgs models with T-parity,

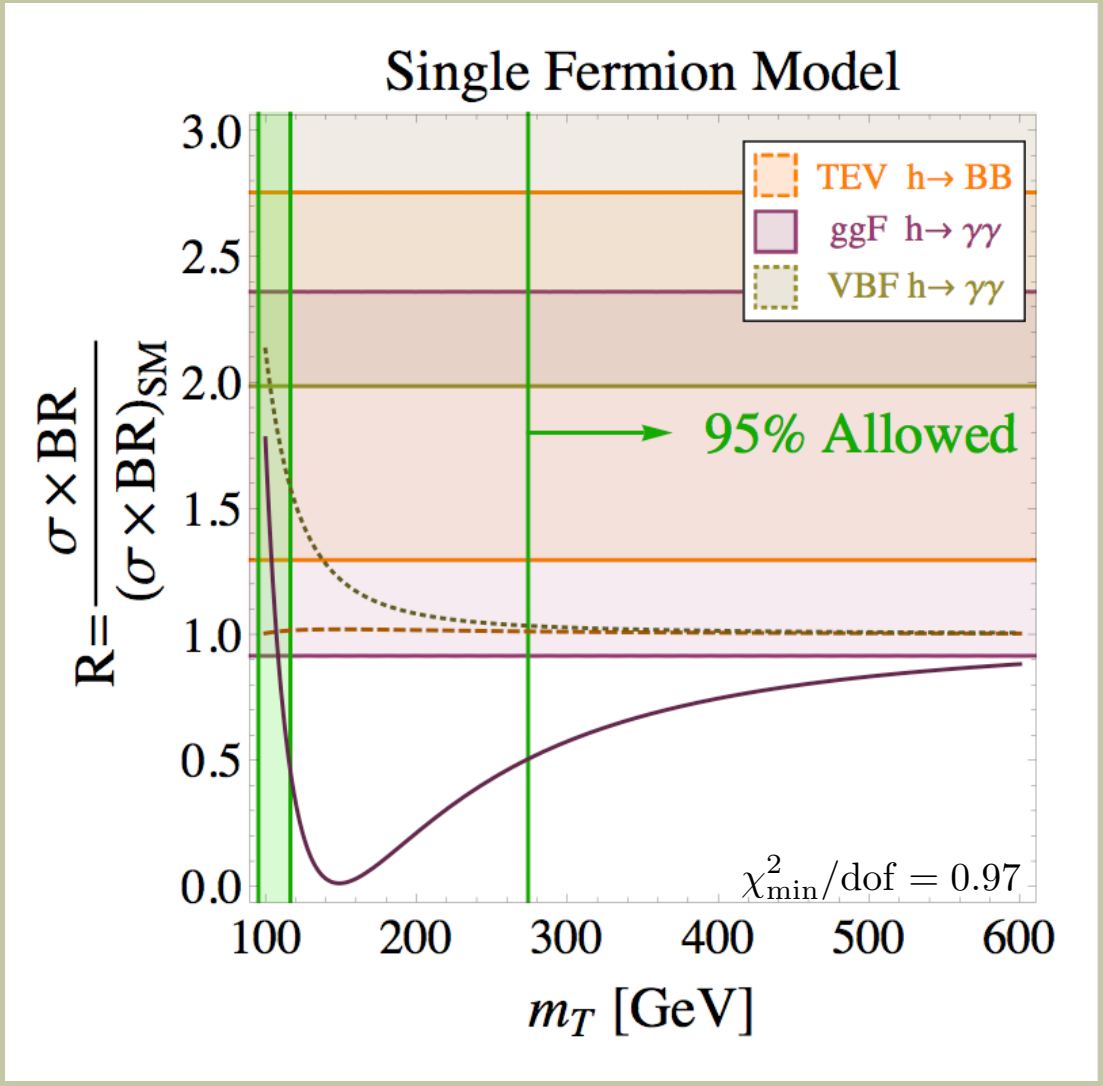
$$\frac{c_g}{c_{g,\mathrm{SM}}} = \frac{c_\gamma}{c_{\gamma,\mathrm{SM}}} \simeq 1 - \frac{m_t^2}{m_T^2}\,, \qquad c_V = c_b = 1$$

- Due to non-renormalizable terms, contribution is opposite to that of top,

$$h \to gg \downarrow \qquad h \to \gamma\gamma \uparrow$$



Fermionic Top Partner



- Bounds from direct searches are better, 400-500 GeV, but are model dependent (T→bW and T→t + MET)

Another Example:

(Preliminary)

Fourth Generation SM is Excluded!

(for a 125 GeV Higgs)

[E. Kuflik, Y. Nir, TV]

The Effect of SM4

- The effect of additional quarks and leptons is drastic on the Higgs production and decay channels.
- Especially ggF and h→γγ:

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

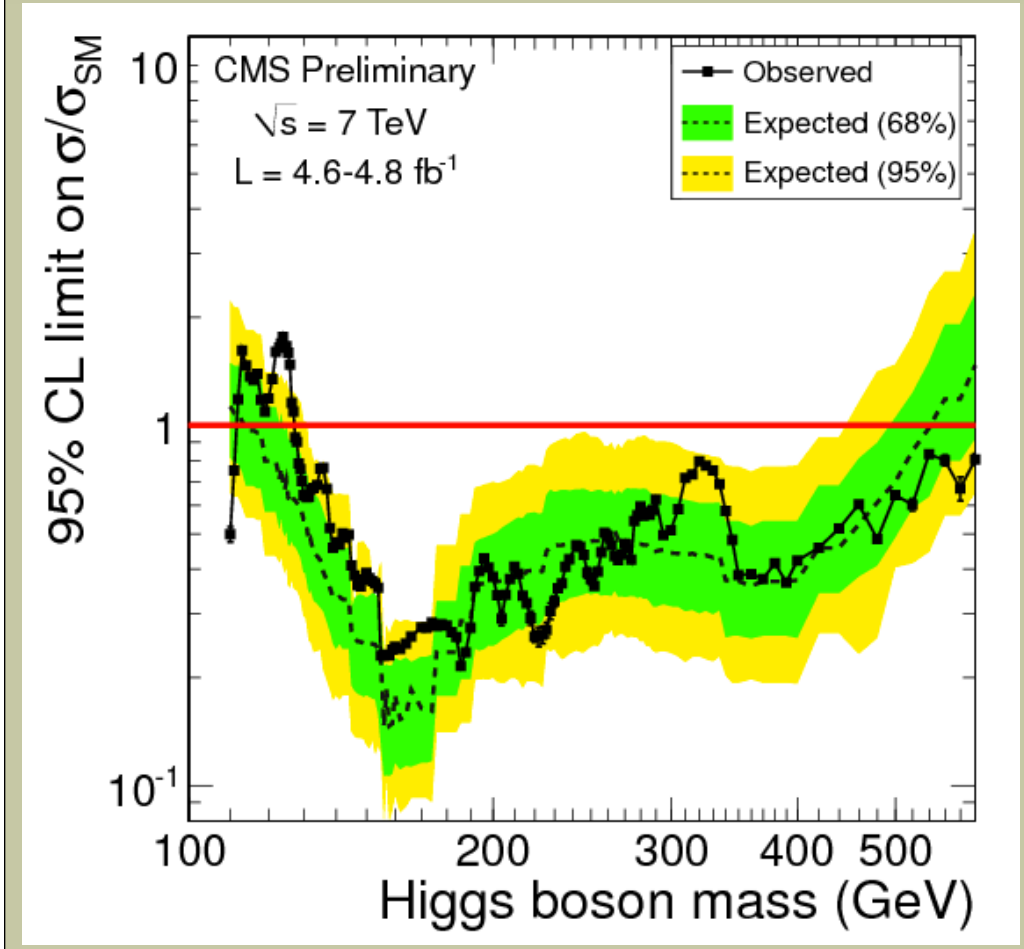
$$\Gamma_{h\to\gamma\gamma} \sim |W - Top - Top' - Bottom' - Tau' - 2Loops|^2 \sim \frac{1}{100} \times \mathrm{SM}$$

[Denner et al., 2011]

- Tree level channels don't change much.
- Branching fractions then behave as above if 4th neutrino is heavy.
- All BR's are uniformly suppressed for a light 4th neutrino (an invisible channel).

But **ratios** of BR's are independent of 4th neutrino and are strongly deformed, contradicting the current results.

SM4 Higgs and Direct Searches

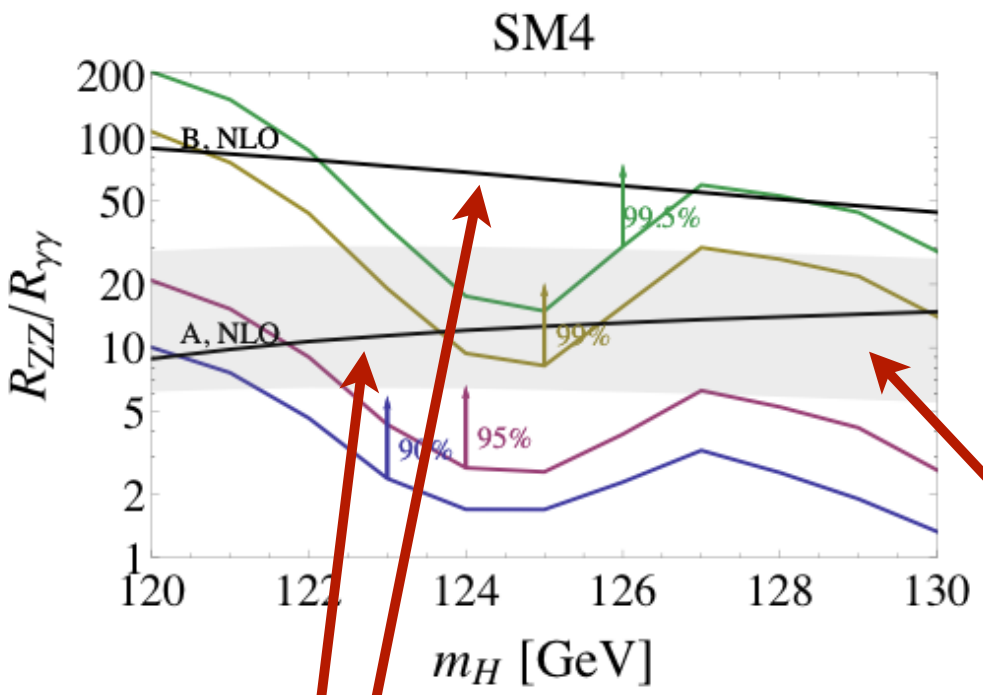


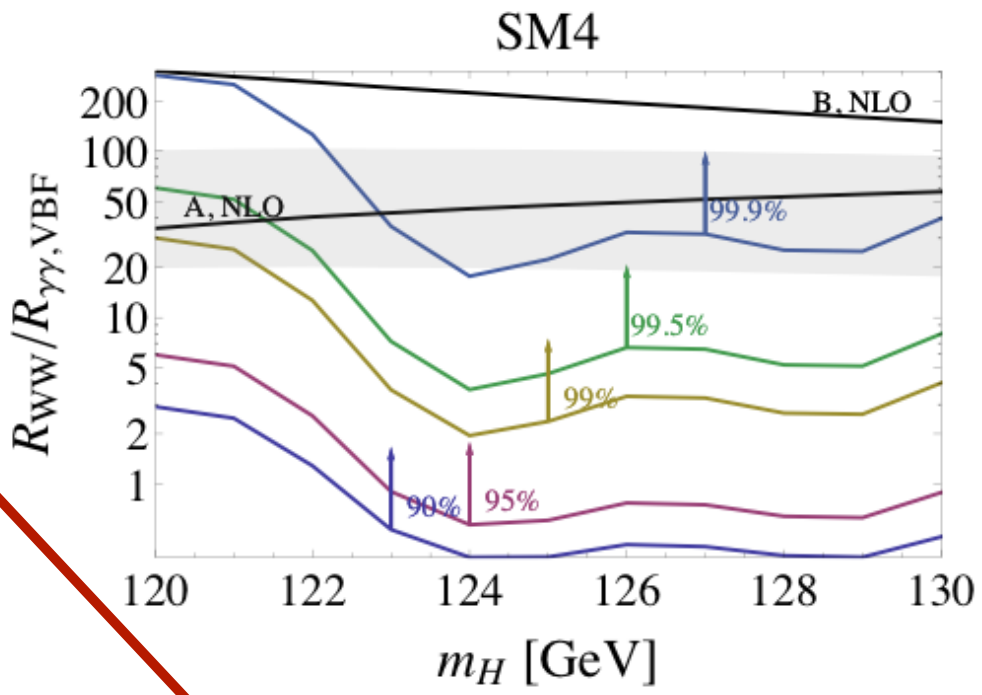
4th generation quarks: Summary

Exp.	Channel	$\int L\,dt$ [fb^{-1}]	Mass limit
ATLAS	$Qq \to Wqq'$	1.0	$m_Q > 900$ GeV
ATLAS	$Qq \to Zqq'$	1.0	$m_Q > 760$ GeV
ATLAS	$QQ \to (Wq)(Wq)$	1.0	$m_Q > 350$ GeV
CMS	chiral $Q \to WbX$	1.1	$m_Q > 490$ GeV
ATLAS	$TT \to (Wb)(Wb)$	1.0	$m_T > 404$ GeV
ATLAS	$TT \to (tA_0)(tA_0) \to l\,X$	1.0	$m_T > 420$ GeV
CMS	$TT \to (Wb)(Wb) \to llX$	4.7	$m_T > 552$ GeV
CMS	$TT \to (Wb)(Wb) \to lX$	4.7	$m_T > 560$ GeV
CMS	$TT \to (Zt)(Zt)$	1.1	$m_T > 475$ GeV
ATLAS	$BB \to (Wt)(Wt) \to ljjjjjX$	1.0	$m_B > 480$ GeV
ATLAS	$BB \to (Wt)(Wt) \to llX$ (SS l)	1.0	$m_B > 450$ GeV
CMS	$BB \to (Wt)(Wt)$	4.6	$m_B > 600$ GeV

- SM4 Higgs search does not exclude the model for 125 GeV Higgs, precisely because there is an excess of events
- Either way, exclusions are model dependent since heavy 4th neutrino is assumed or specific decay modes.

Using the SM Higgs Searches..



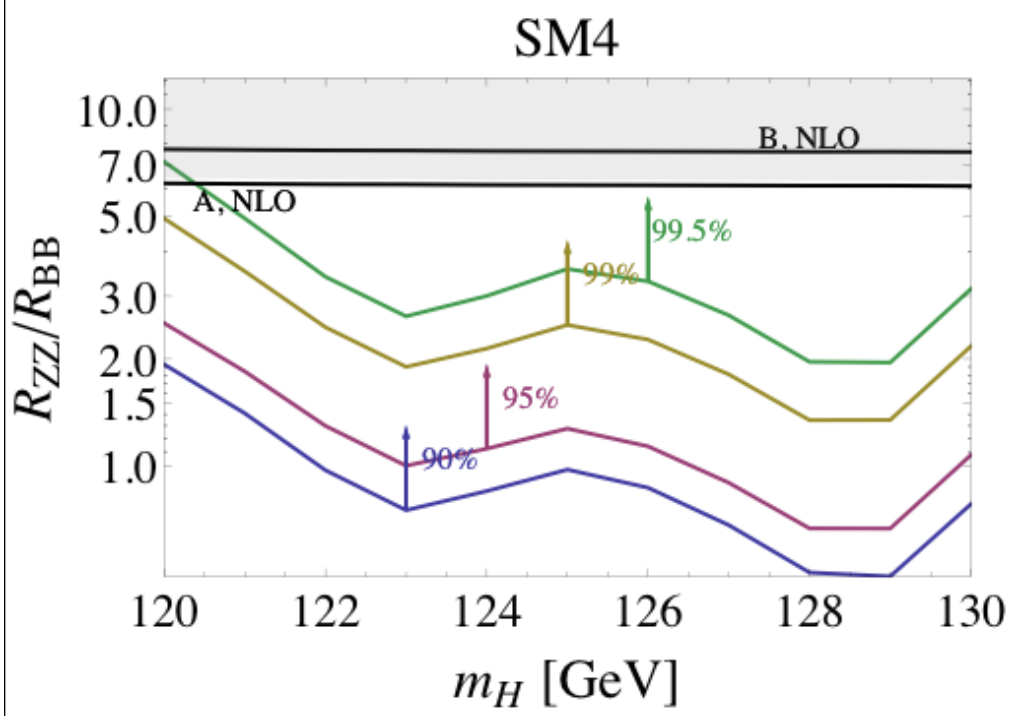


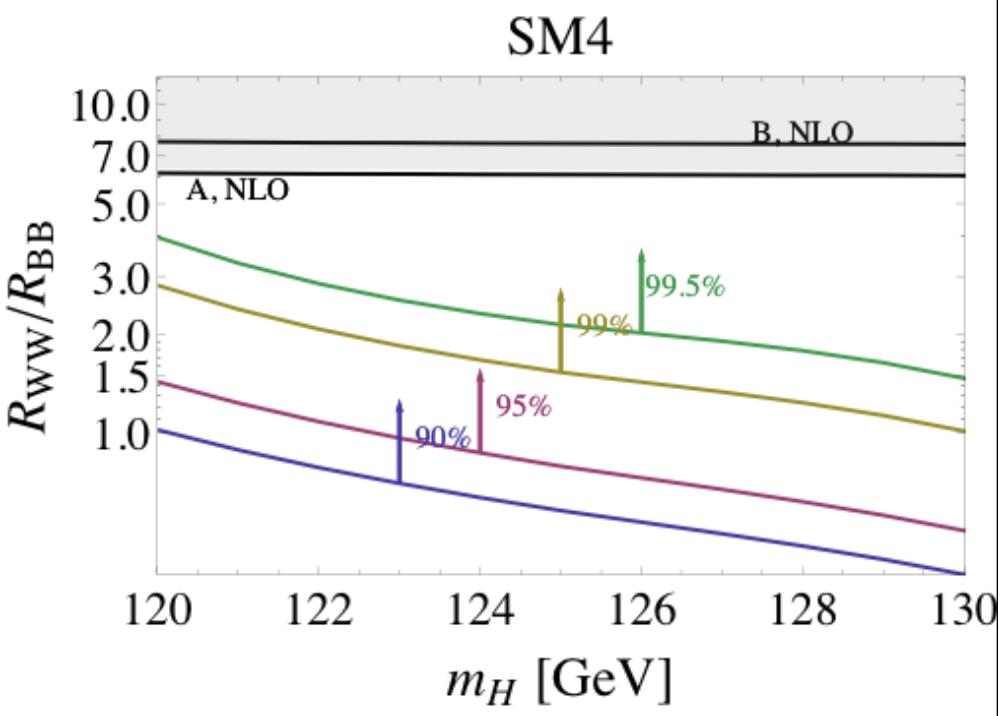
Spectrum A: $m_{t'} = 500\text{GeV}, \quad m_{b'} = 450\text{GeV}$
$m_{l'} = 450\text{GeV}, \quad m_{\nu'} = 375\text{GeV}$

Spectrum B : $m_{t'} = 650\text{GeV}, \quad m_{b'} = 600\text{GeV}$
$m_{l'} = 600\text{GeV}, \quad m_{\nu'} = 600\text{GeV}$

HDecay scan - conservative $\gamma\gamma$ rate.

Using the SM Higgs Searches..





Conclusions

- Higgs searches encode lots of information on NP.
- Already interesting results can be extracted..
- **Experimentalists** should provide the allowed region on the Higgs effective action.
- **Theorist** should map their favorite theories on to the same action.

Together we will, once again, confirm the SM...

Or will we??....

[I'm not around, but will be happy to discuss further: tomerv@post.tau.ac.il

skype: t.volansky

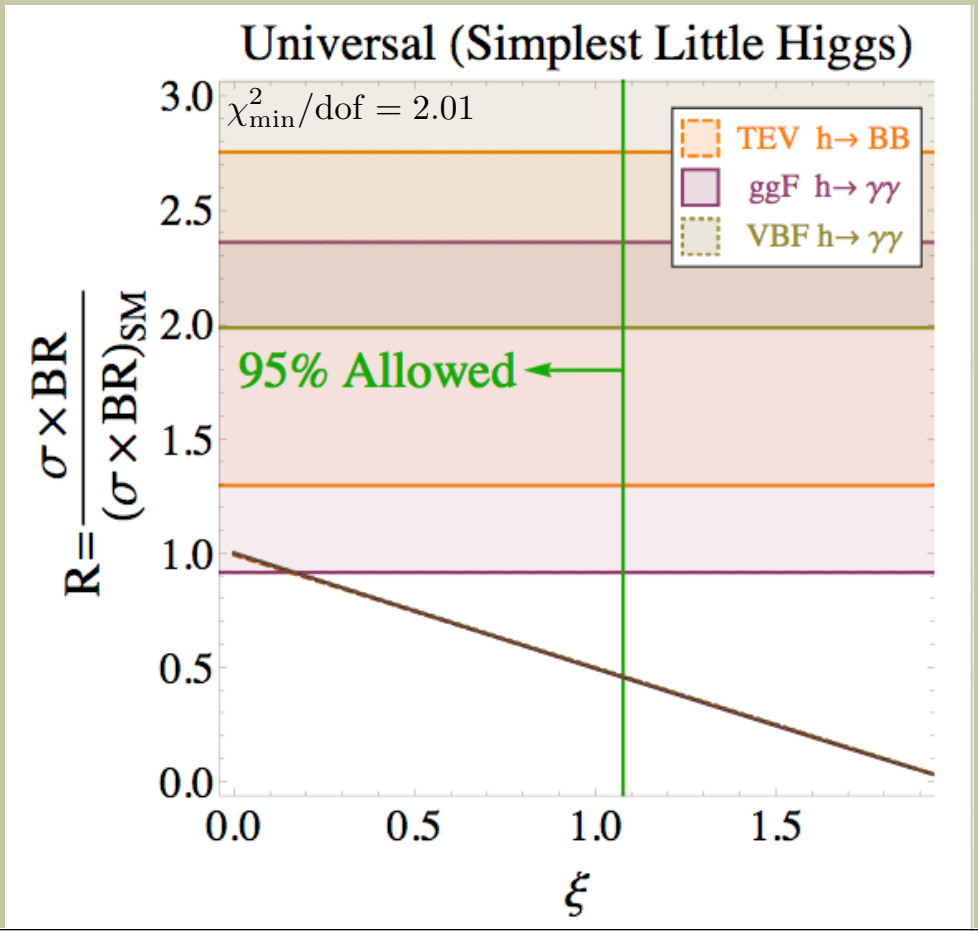
Extras

Simplest Little Higgs

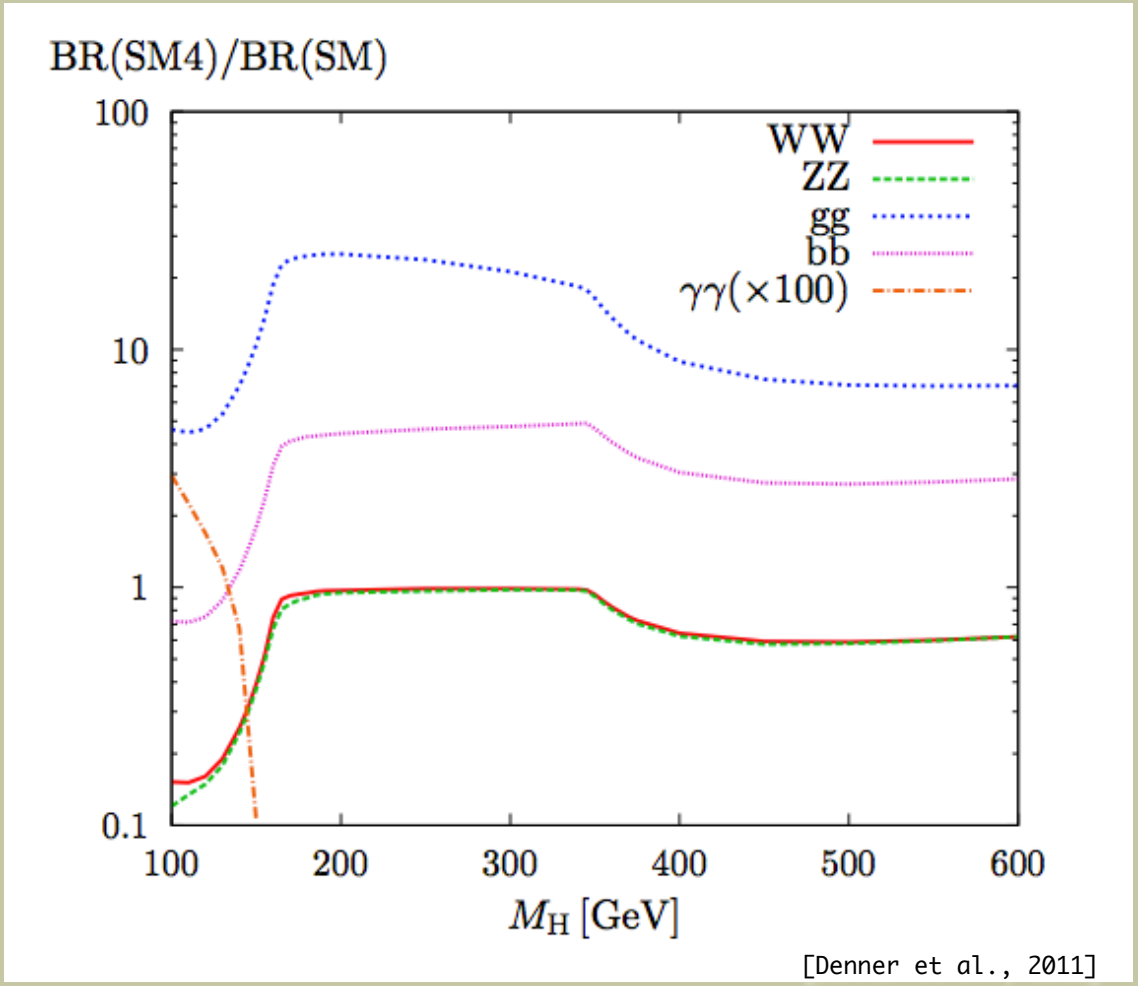
- Another Little-Higgs inspired scenario:

$$-\mathcal{L}_{top} = yf\sin(|H|/f)tt^c + yf\cos(|H|/f)Tt^c + M'TT^c + \text{h.c.}$$

$$\frac{c_g}{c_{g,\text{SM}}} = \frac{c_\gamma}{c_{\gamma,\text{SM}}} = c_V = c_b = \sqrt{1 - \frac{v^2}{2f^2}}$$



The Effect of SM4



[Denner et al., 2011]