A 125 GeV Higgs: From naturalness to fourth generation and beyond

Eric Kuflik
Tel Aviv University

Dean Carmi, Adam Falkowski, EK, Tomer Volansky [1202.3144]
EK, Tomer Volansky, Yossi Nir [1204.1975]

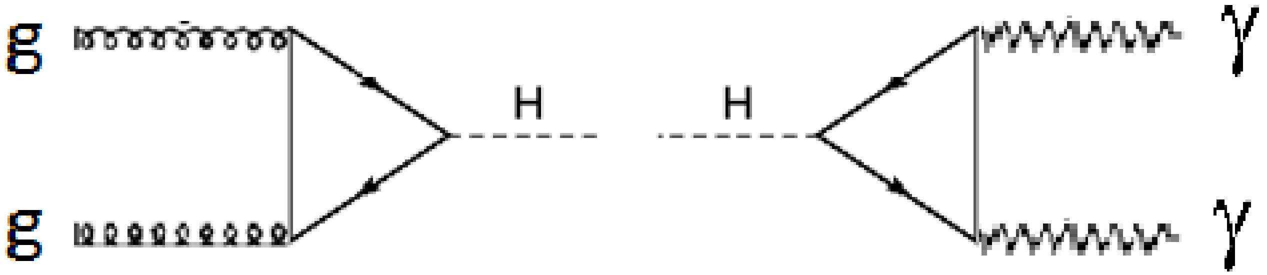
Outline

- Naturalness vs. Discovery
- Higgs at the LHC
- Constraints on BSM physics (SUSY, 4^{th} generation, …)

Learning from the Higgs

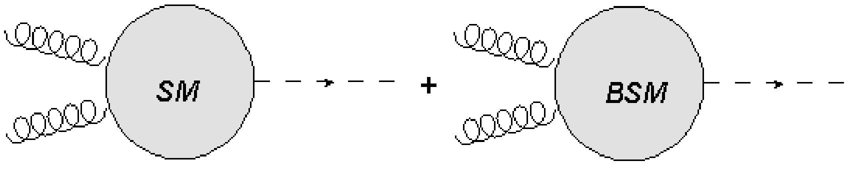
The Higgs is an excellent tool to study new physics and hierarchy problem

- Discovering the Higgs is a loop-effect



- No loop suppression relative to Standard Model to see new physics

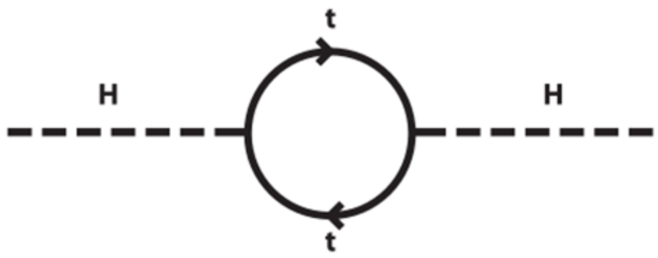
- Very sensitive to new physics



Chronic Hierarchy Problem Slide

- Hierarchy problem dominated model building for last 30 years.

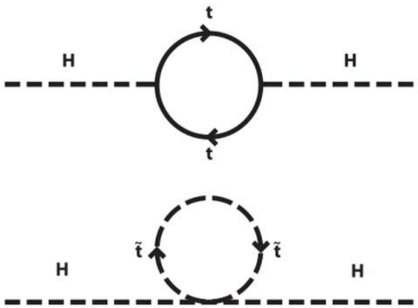
Why is the weak force so much stronger than gravity?

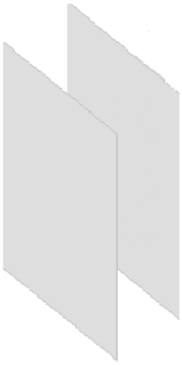


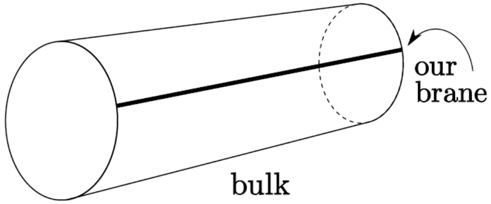
$$\delta m_h^2 = \frac{3 m_t^2}{2\pi^2 v^2}\,\Lambda^2$$

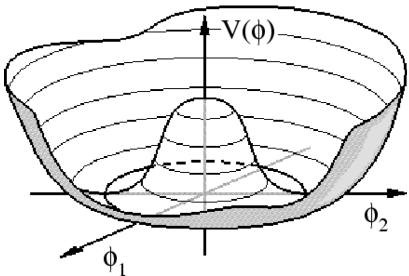
Solutions to the Hierarchy Problem

- 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

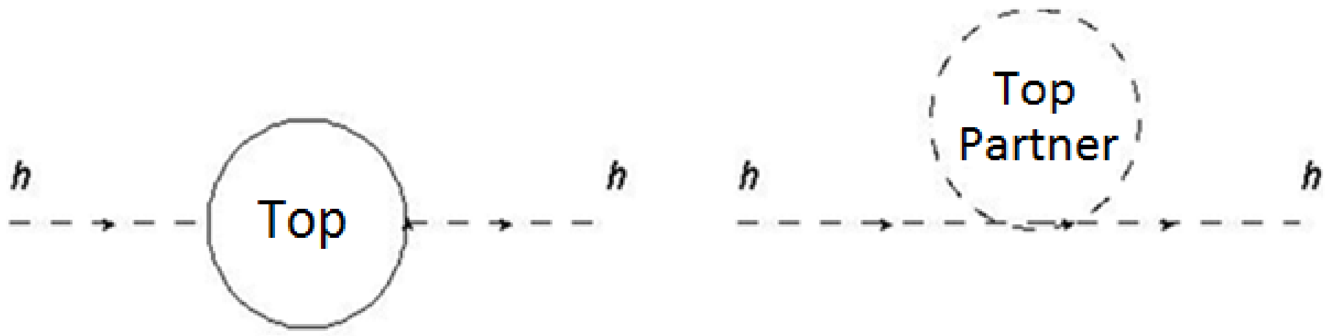
- Where is the new physics that was promised to me?
  - All these theories predict new physics at the TeV scale, then where is it?
  - All existing models introduce a multitude of new particles, which typically require a few percent tuning to avoid constraints
  - Wasn't low-energy supersymmetry coming 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.

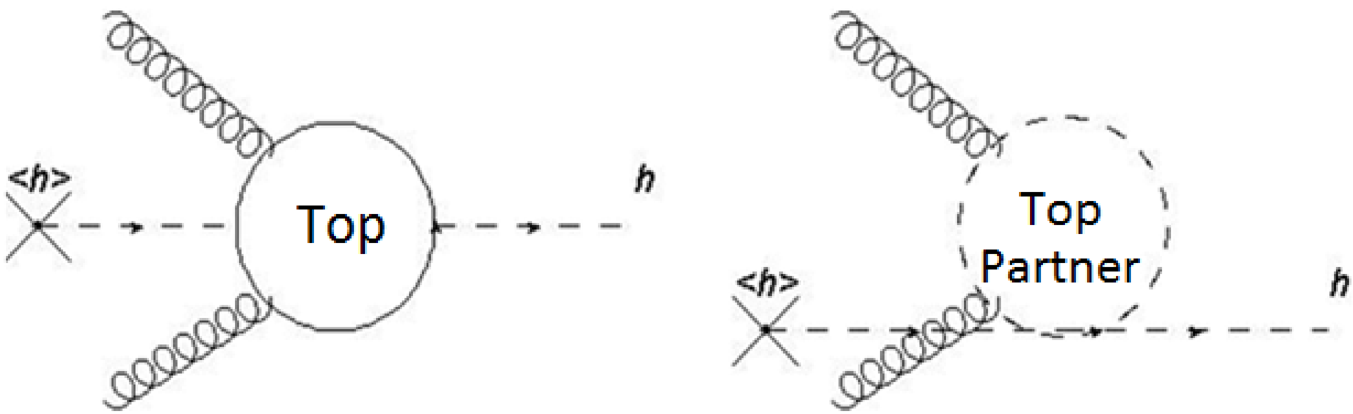
- Precision Higgs is telling us how natural our world is.

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



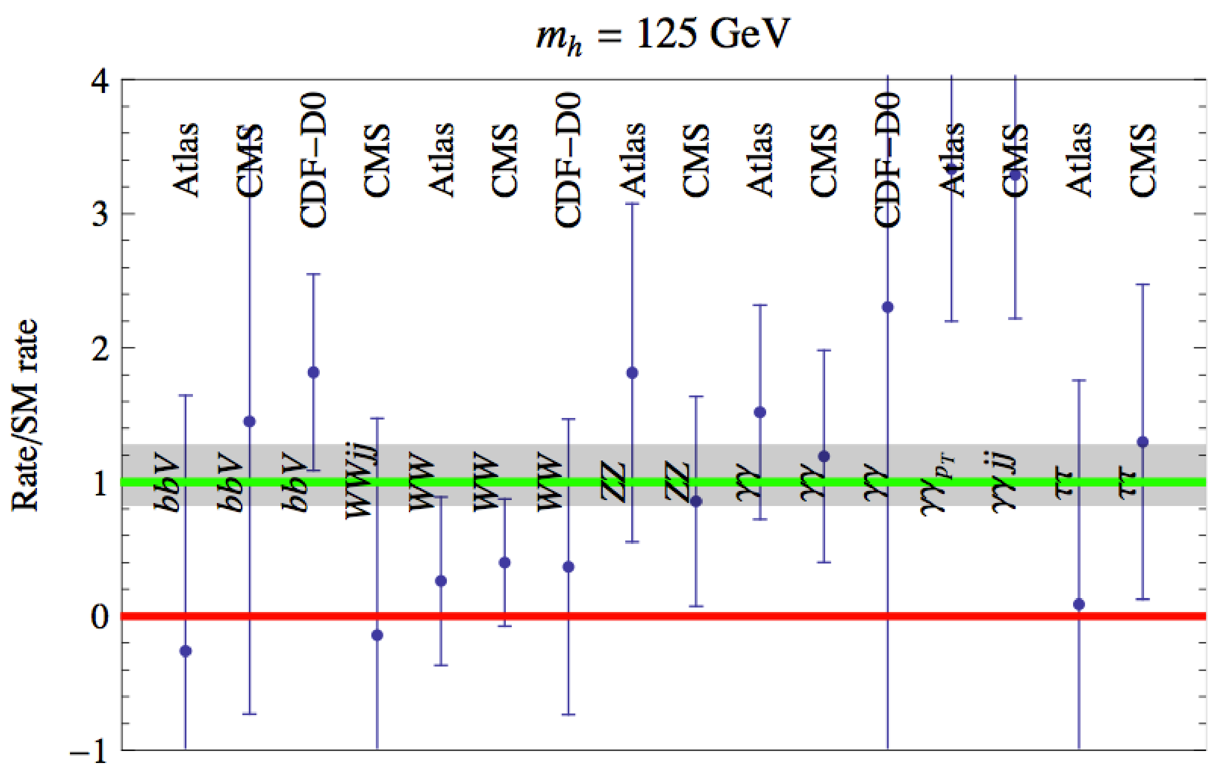
Changes Higgs rates.

With the same couplings

Higgs at the LHC

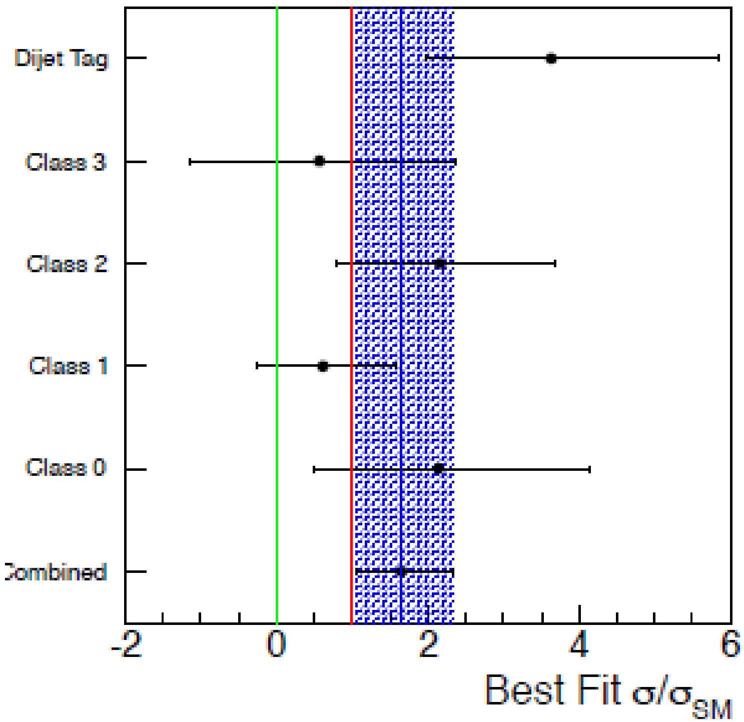
- The SM Higgs with mass around 125 GeV has many decay channels that are potentially observable at the LHC
  - Now: $H \to ZZ^{*}$ and $H \to \gamma\gamma$
  - Soon: $H \to WW^{*}$
  - Later: $H \to \tau\tau$ and $H \to b\bar{b}$
- Also different production channels can be isolated
  - Now: gluon fusion
  - Soon: vector boson fusion
  - Later: associated production with W/Z and $t\bar{t}$
- Rich Higgs physics available in the near future.

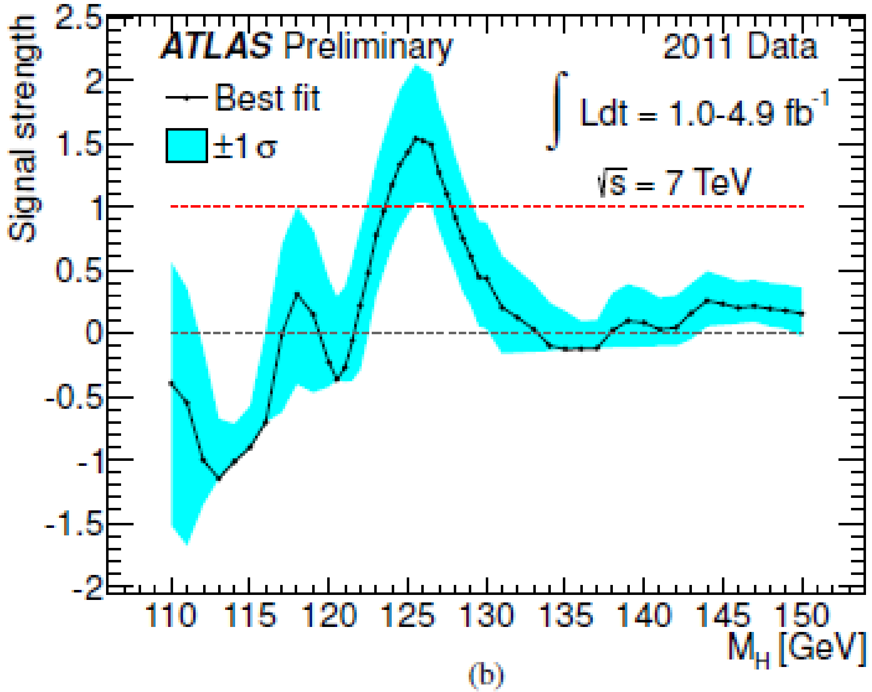
- Most relevant LHC search channels updated to 5 fb-1 in ATLAS and CMS
- Currently most information can be extracted from $H \rightarrow ZZ^*$ *and* $H \rightarrow \gamma\gamma$
- Strong hints for 125 GeV Higgs, while other mass ranges are roughly excluded.



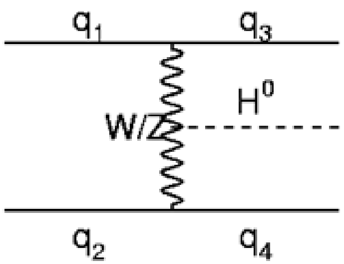
[Giardino et al., 2012]

$h \to \gamma\gamma$

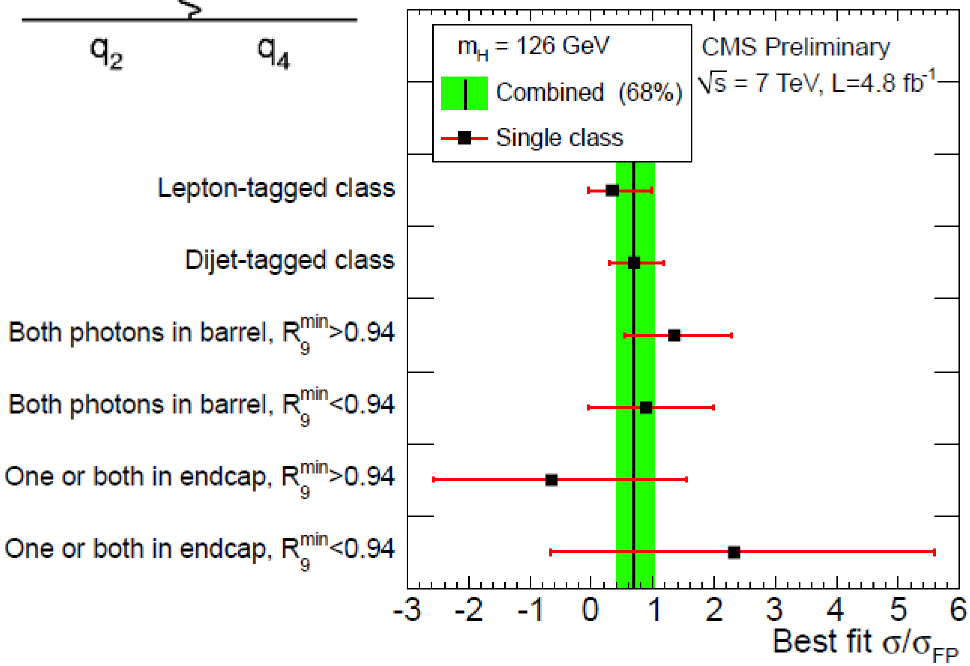


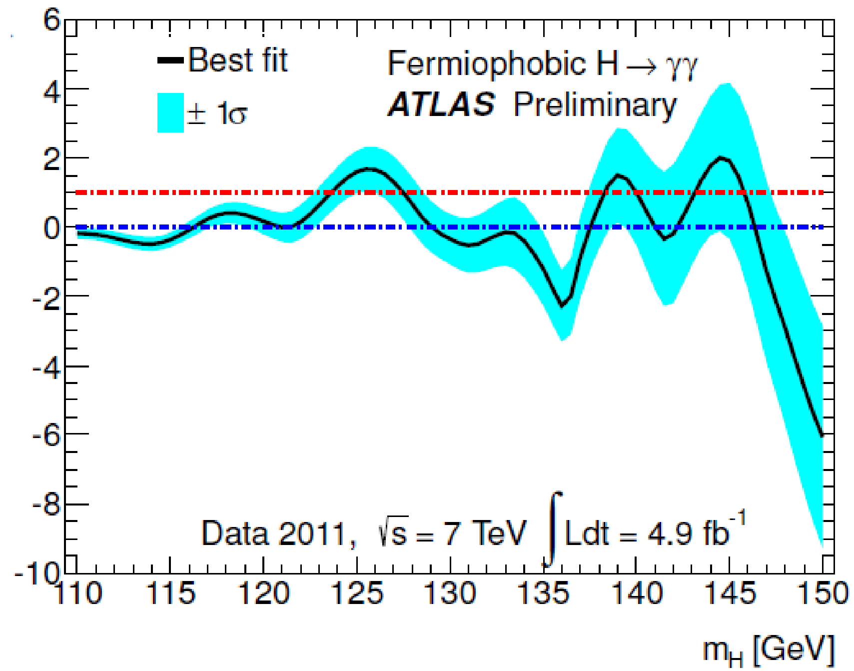


- Significant background, but great mass resolution
- Both ATLAS and CMS observe an excess, ATLAS: 126 GeV and CMS: 124 GeV.
- In both cases the best fit cross section at the peak exceeds the SM value, though well within uncertainties.
- CMS observes an excess in the dijet class, which is expected to be dominated by VBF production mode



$VBF \rightarrow h \rightarrow \gamma\gamma$

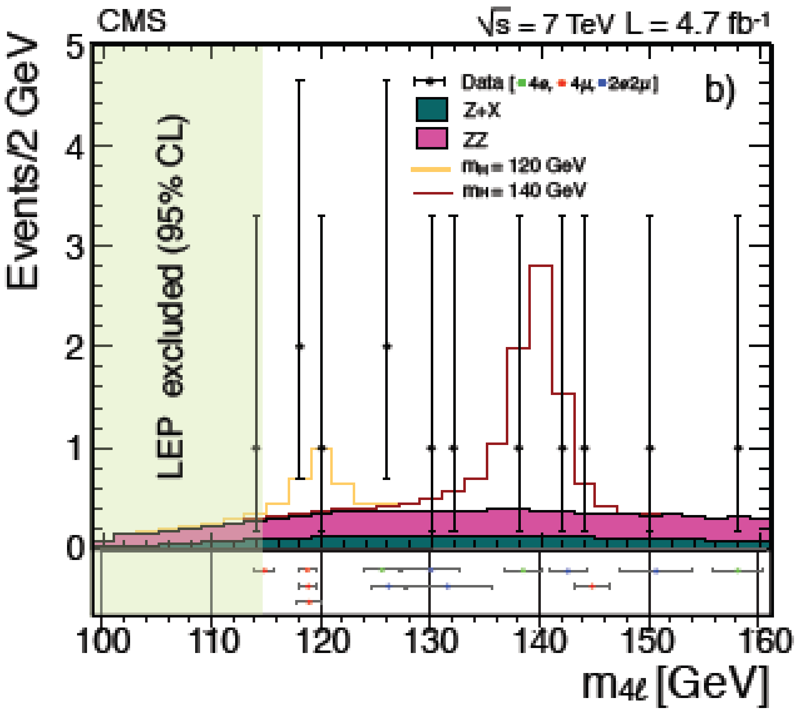


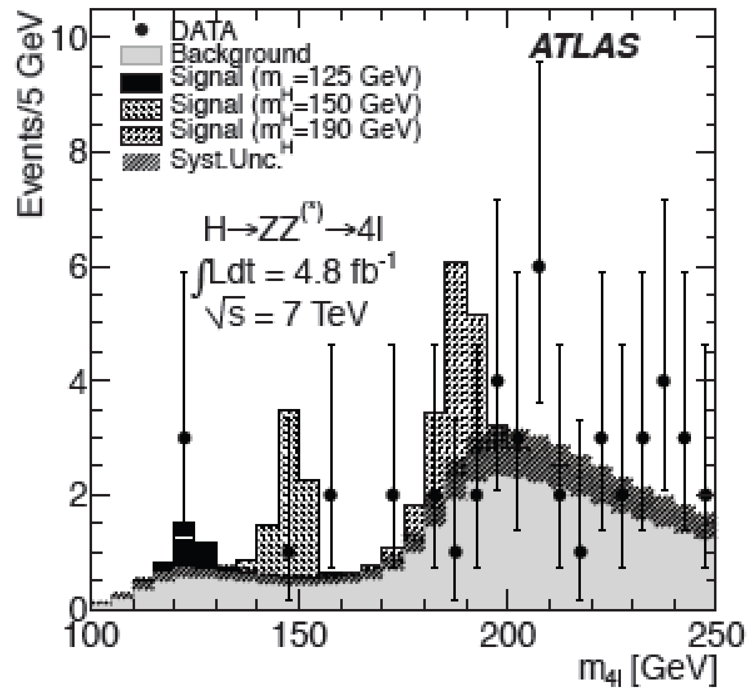


- Fermiophobic Higgs bosons motivated searches
- Can only be produced through vector boson fusion (VBF) and associated production with vector bosons (VH, V = W; Z).
- Both observe an excess in inclusive dijet channel dominated by VBF production mode, corresponding to cross section well exceeding the SM one (though, again, uncertainties are still large)

3.3 +- 1.1 x SM rate

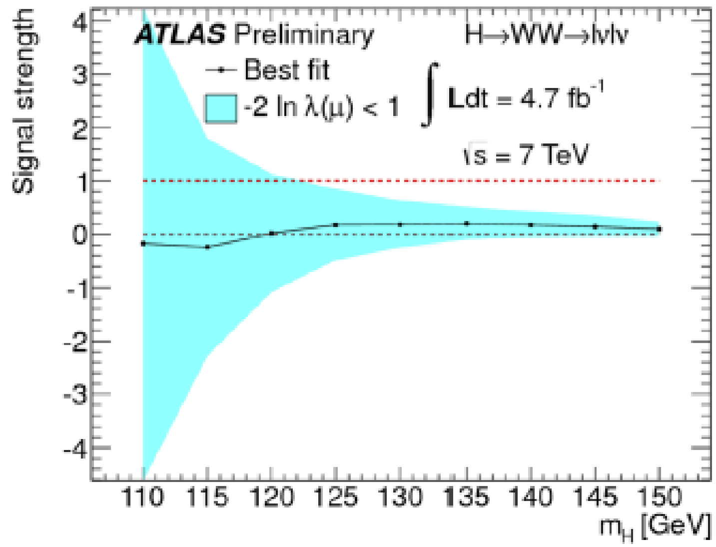
$h \rightarrow ZZ$





- Very low background, great mass resolution
- ATLAS has 3 events at 124 GeV
- CMS has 2 events at 126 GeV

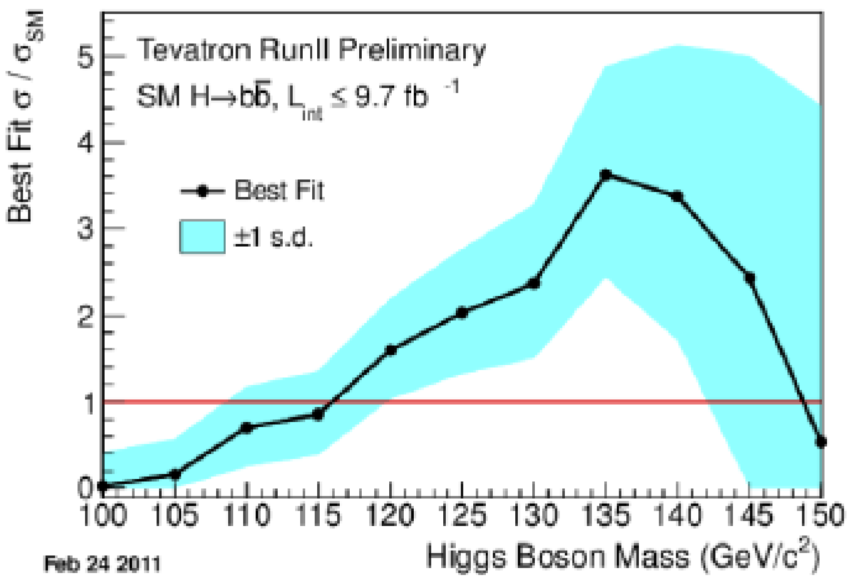
$h \to WW$

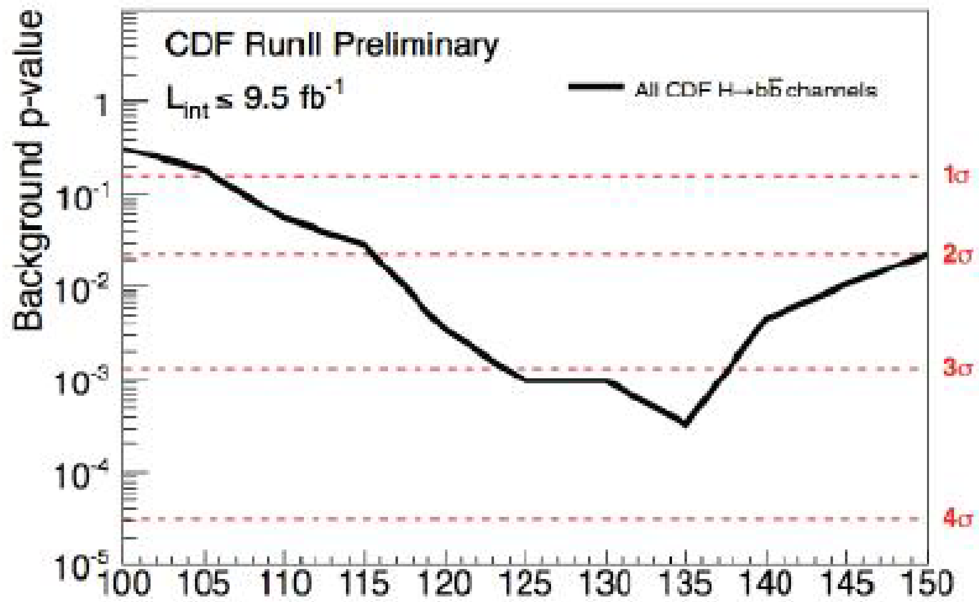


		Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
0-jet	$m_H = 125$ GeV	25 ± 7	110 ± 12	12 ± 3	7 ± 2	5 ± 2	13 ± 8	27 ± 16	173 ± 22	174
	$m_H = 240$ GeV	60 ± 17	432 ± 49	24 ± 3	68 ± 15	39 ± 9	8 ± 2	36 ± 24	607 ± 63	629
1-jet	$m_H = 125$ GeV	6 ± 2	18 ± 3	6 ± 3	7 ± 2	4 ± 2	6 ± 1	5 ± 3	45 ± 7	56
	$m_H = 240$ GeV	23 ± 9	99 ± 22	8 ± 1	73 ± 27	35 ± 19	6 ± 2	7 ± 7	229 ± 55	232
2-jet	$m_H = 125$ GeV	0.4 ± 0.2	0.3 ± 0.2	negl.	0.2 ± 0.1	negl.	0.0 ± 0.1	negl.	0.5 ± 0.2	0
	$m_H = 240$ GeV	2.5 ± 0.6	1.1 ± 0.7	0.1 ± 0.1	2.6 ± 1.3	0.3 ± 0.3	negl.	0.1 ± 0.1	4.2 ± 1.7	2

- Significant background, poor mass resolution, better for exclusion than discovery
- No excess?
  - Custodial symmetry: if excess in ZZ (or VBF) then there should be an excess in WW.

$h \to bb$



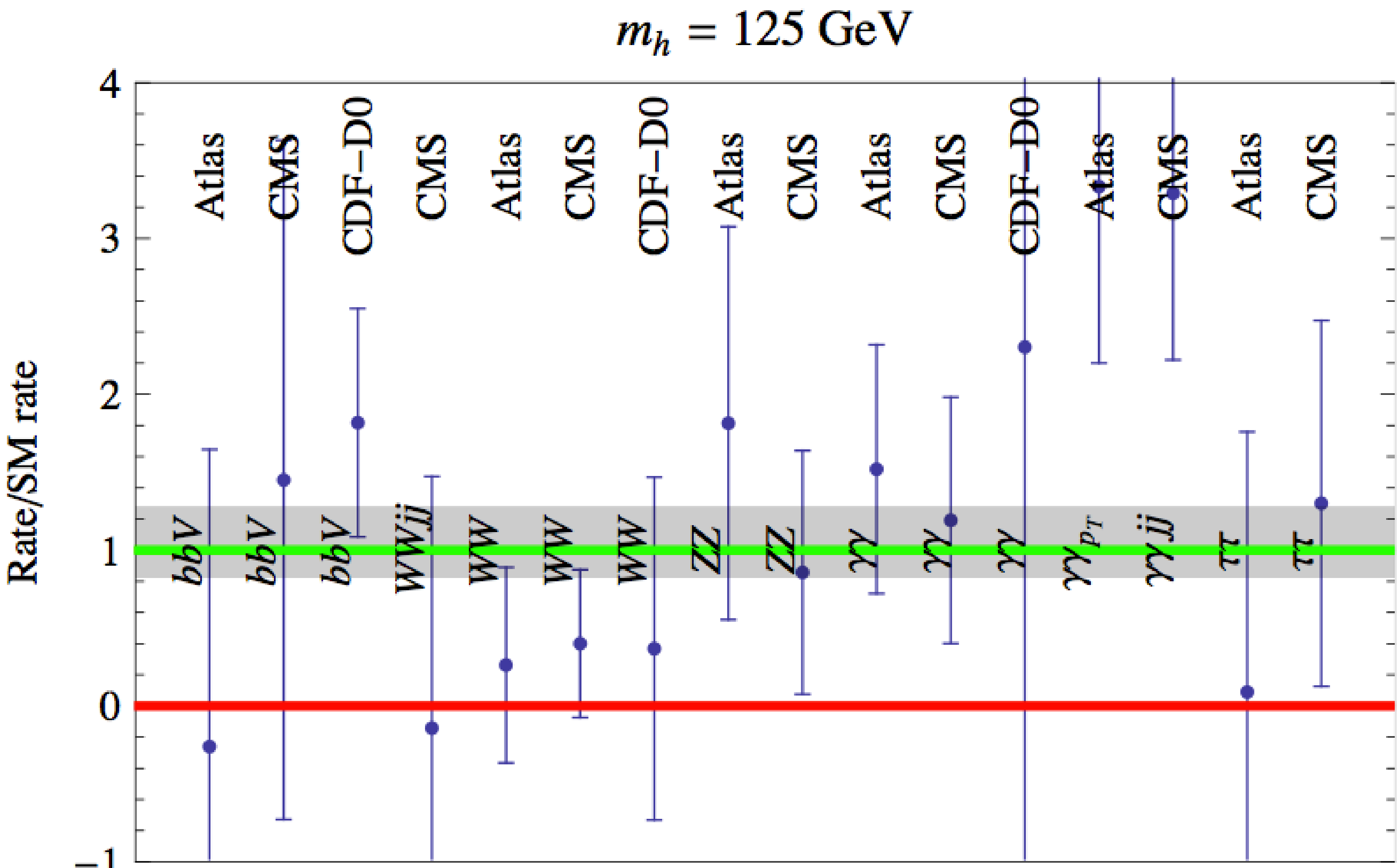


- Points to a somewhat enhanced rate in *VH* production channel
- Doesn't strongly favor any mass between 120 and 135 GeV– the likelihood is flat.

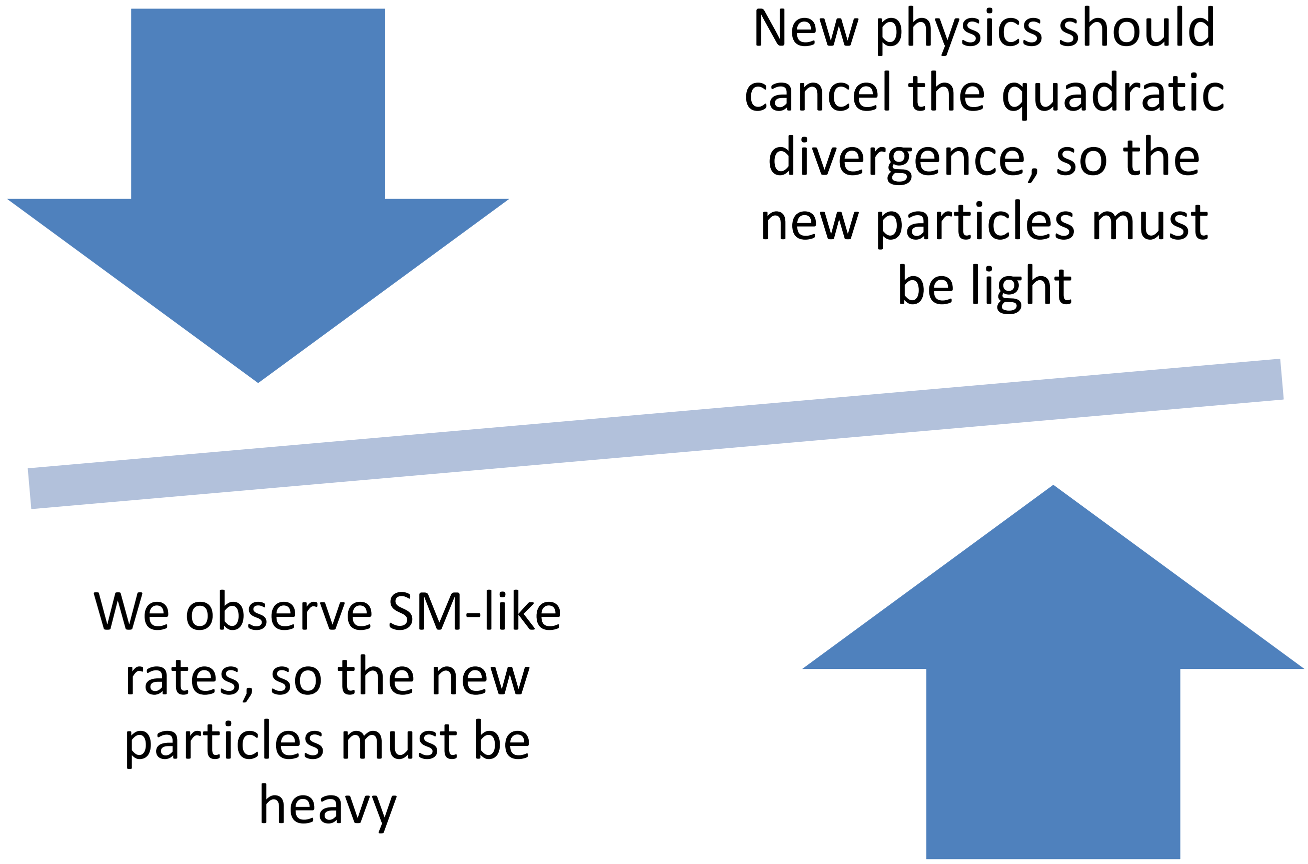
The Higgs boson has been ~~discovered~~ seen,

and has mass near 125 GeV

A Standard Model Higgs?



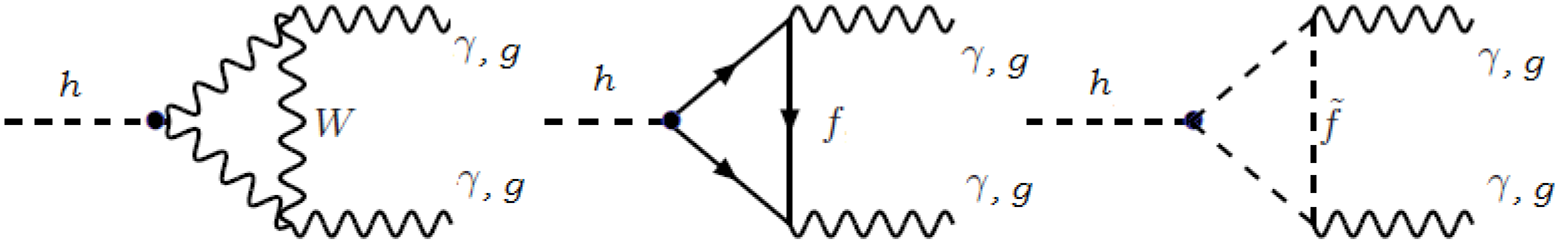
[Giardino et al., 2012]



More little hierarchy problems

will become stronger with more data

Technical Details



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

$$\tau_i = m_h^2/4m_i^2$$

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

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

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

EFT Approach

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

- We will find the region of effective theory parameter space favored by Higgs data.
- Interesting to check whether the current LHC data are consistent with the SM Higgs
- Also interesting, whether they favor or disfavor any particular BSM scenario.
- Of course at this stage one cannot make very strong statements about Higgs couplings (some of you don't even think Higgs has been discovered)
- Consider it a warm-up exercise, in preparation for serious signals
- Recently Carmi [1202.3144] , Azatov [1202.3415], Espinosa [1202.3697], and Giardino [1203.4254]

For $m_h \sim 125$ GeV total Higgs width scales as

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

Assuming $H \to bb$ dominates Higgs widths

$$R_V \equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to ZZ^*)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to ZZ^*)} \simeq \left| \frac{c_g c_V}{c_b} \right|^2 ,$$

$$R_\gamma \equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to \gamma\gamma)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to \gamma\gamma)} \simeq \left| \frac{c_g \hat{c}_\gamma}{\hat{c}_{\gamma,SM} c_b} \right|^2 ,$$

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

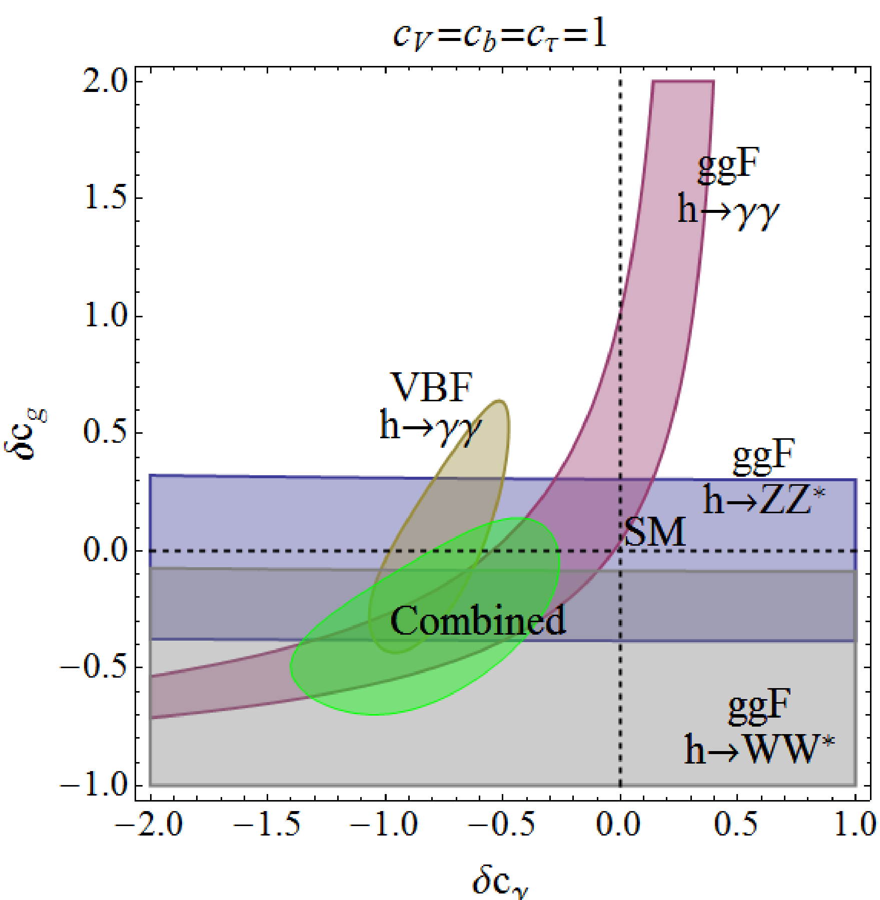
$$R_{\mathrm{Tev}} \equiv \frac{\sigma(p\bar{p} \to Vh)\mathrm{Br}(h \to b\bar{b})}{\sigma_{SM}(p\bar{p} \to Vh)\mathrm{Br}_{SM}(h \to b\bar{b})} \simeq c_V^2 ,$$

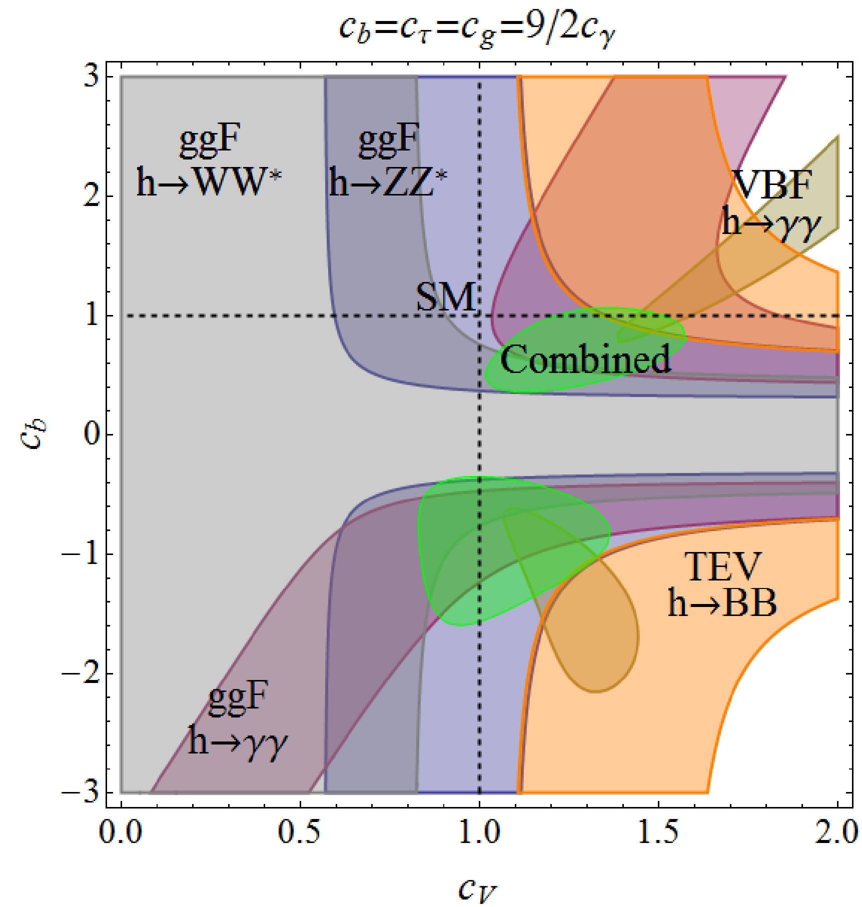
- Only dimension-5 Higgs couplings allowed to vary
- On this plane Tevatron never within 1 sigma band

- Composite Higgs inspired parametrization
- Couplings to fermions and gauge boson allowed to vary independently

New particles in the loops

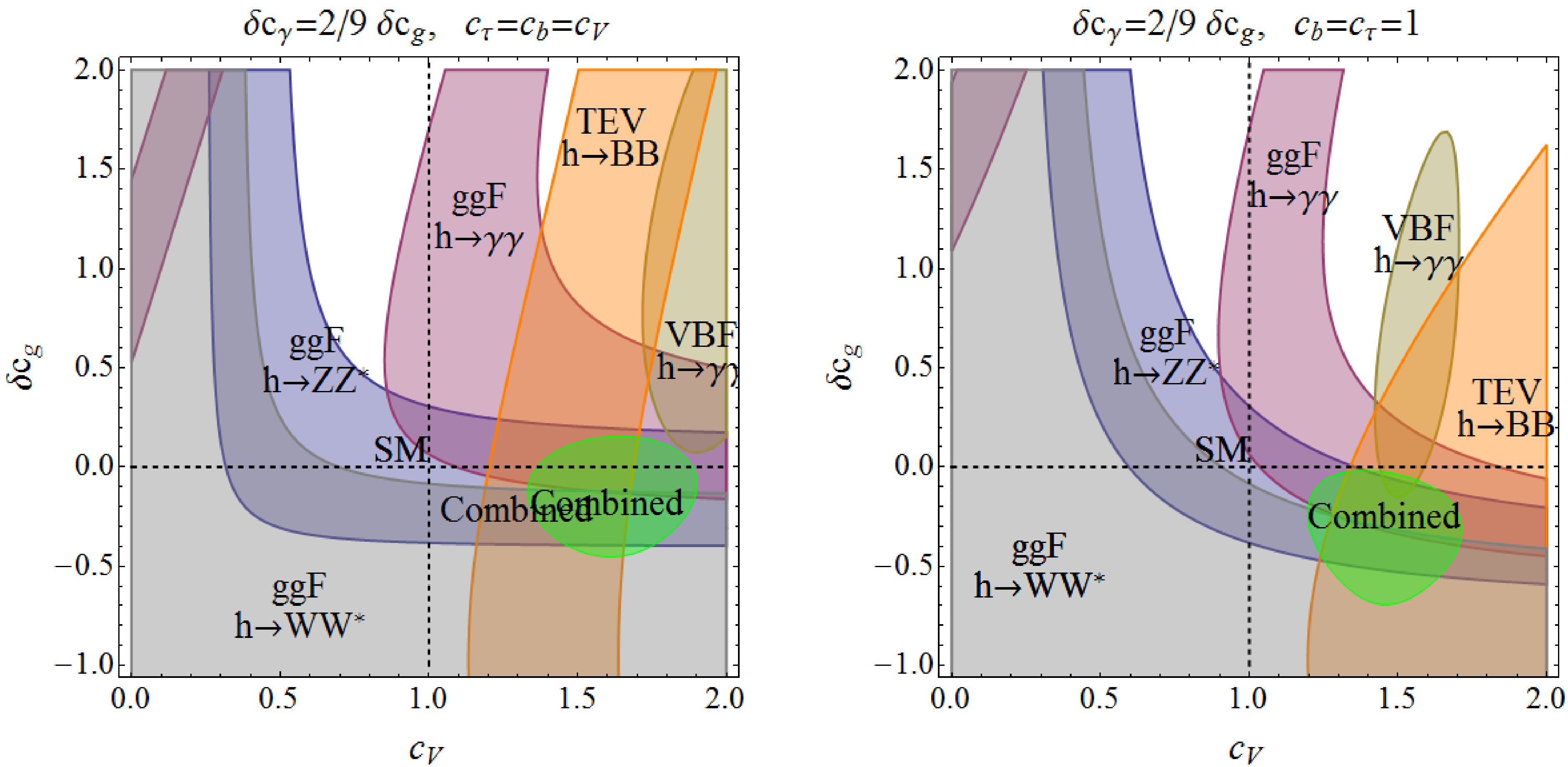
Strongly Interacting Light Higgs





- Top partner models relation $c_\gamma = 2c_g/9$

Top Partner models



Scalar Top Partner

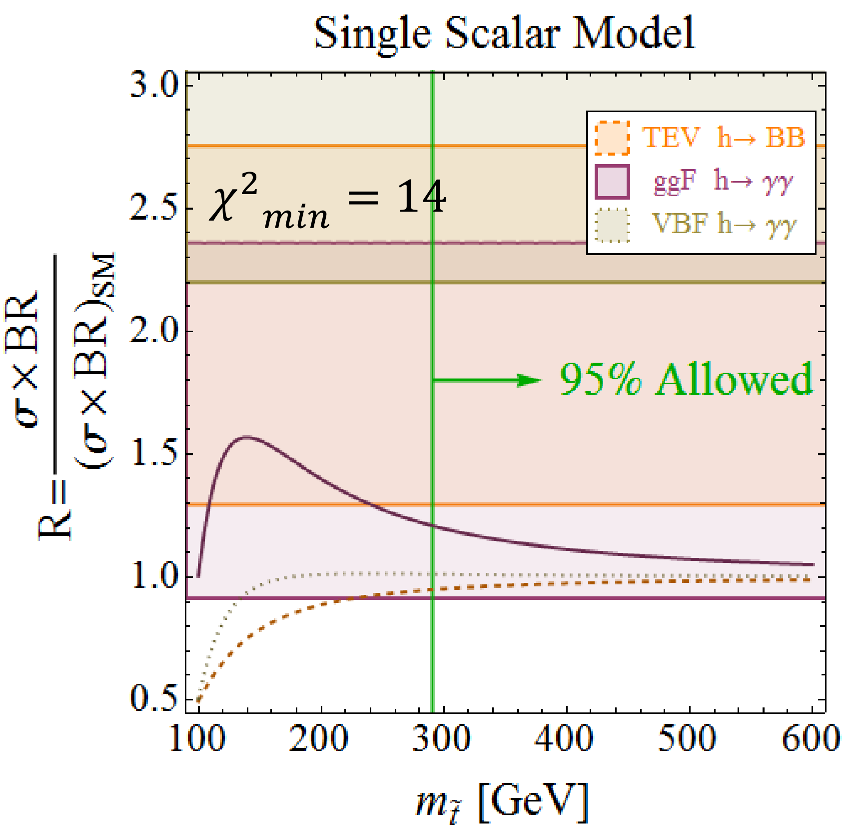
$$b_T \frac{1}{M_T^2(h)} \frac{\partial M_T^2(h)}{\partial h}\Bigg|_{h=v/\sqrt{2}} \Longleftrightarrow STrM^2(h)$$

- 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.



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

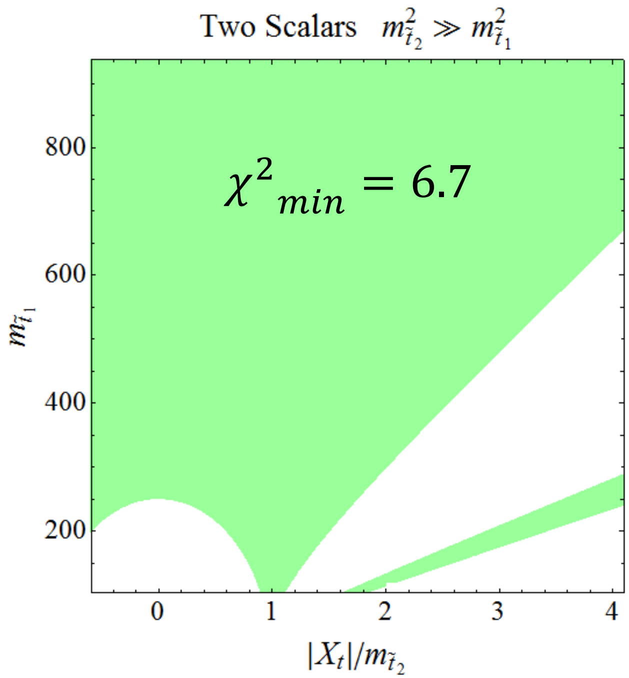
Two Scalar Top Partners - SUSY

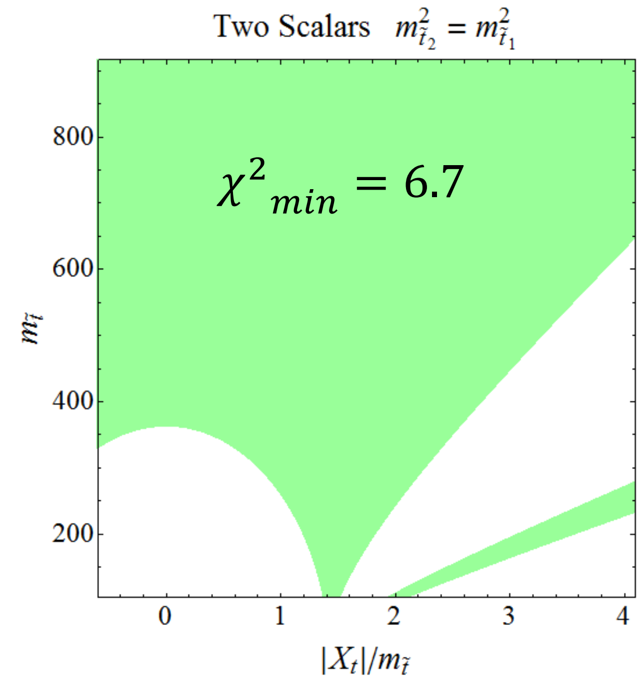
- But with mixing, the signs can change

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

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

- Intersecting 99% CL region. No constraint 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.

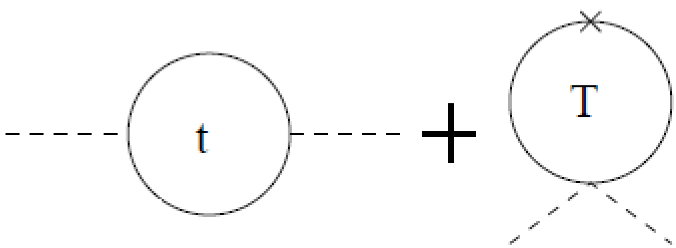




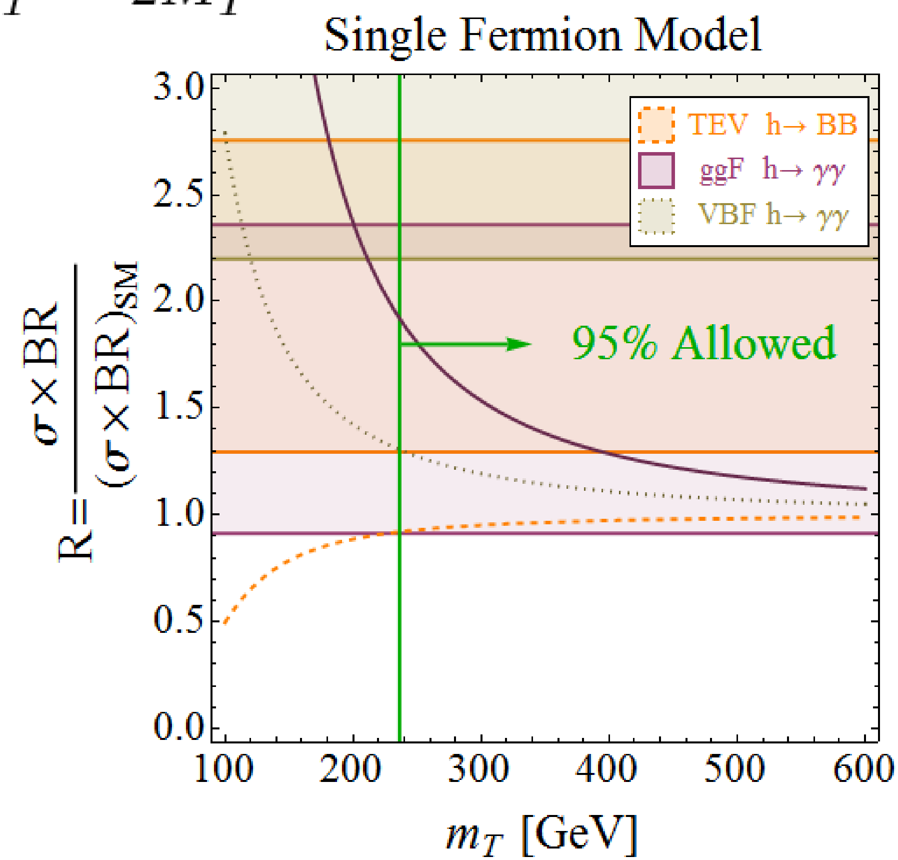
Fermion Partner

- Exactly cancel quadratic divergence:

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



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



Implications of Higgs Searches on the Four Generation Standard Model

with Yossi Nir and Tomer Volansky

[1204.1975]

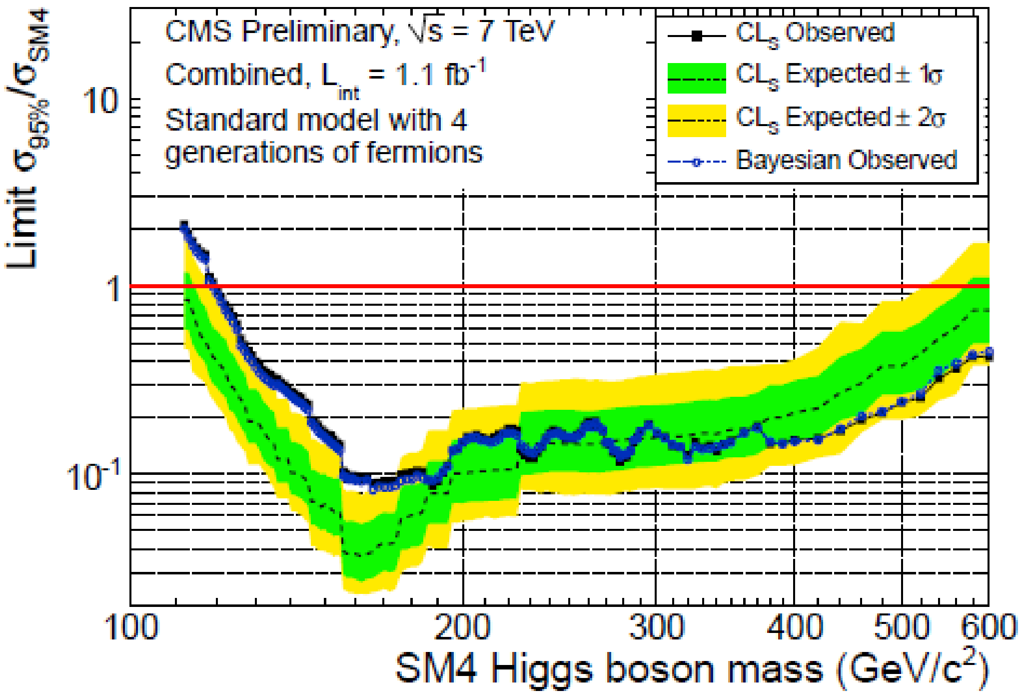
Fourth Generation

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

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

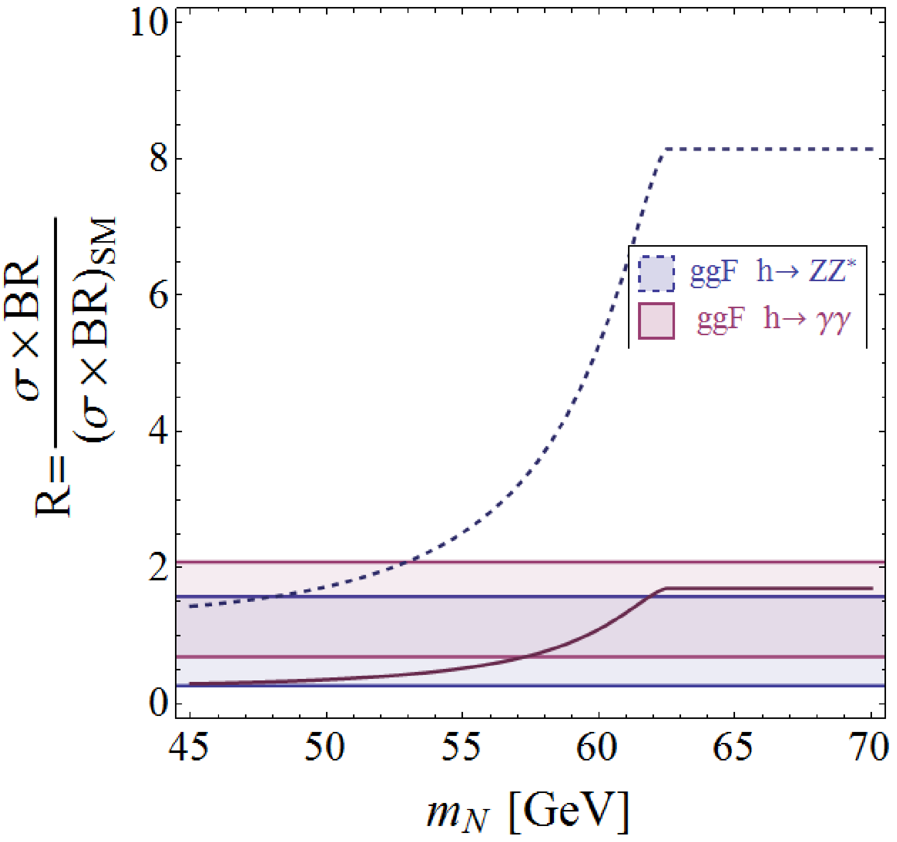
$R_{\gamma\gamma}\sim 1.8$ but $R_{ZZ}\sim 5$

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!

More to the entire story:

- At next-to-leading-order (NLO), the large Yukawa-couplings for heavy fermions can contribute significantly to all widths.
- Complete NLO widths have been calculated by Denner et. Al. [1111.6395] and implemented in HDECAY and Prochecy4f
- For very heavy fermion masses, up to the perturbative limit, the corrections to the decay rates to fermions and heavy gauge bosons can be as large as a factor of 2
  - Tend to increase the width to fermions, while decreasing the widths to WW and ZZ.
- The NLO corrections to $h \to gg$ are found to be less significant.

Not the entire story:

- The LO value of the $h \to \gamma\gamma$ width is already accidentally small due to the destructive interference between the W-boson and fermion loops.
- NLO corrections are very large!

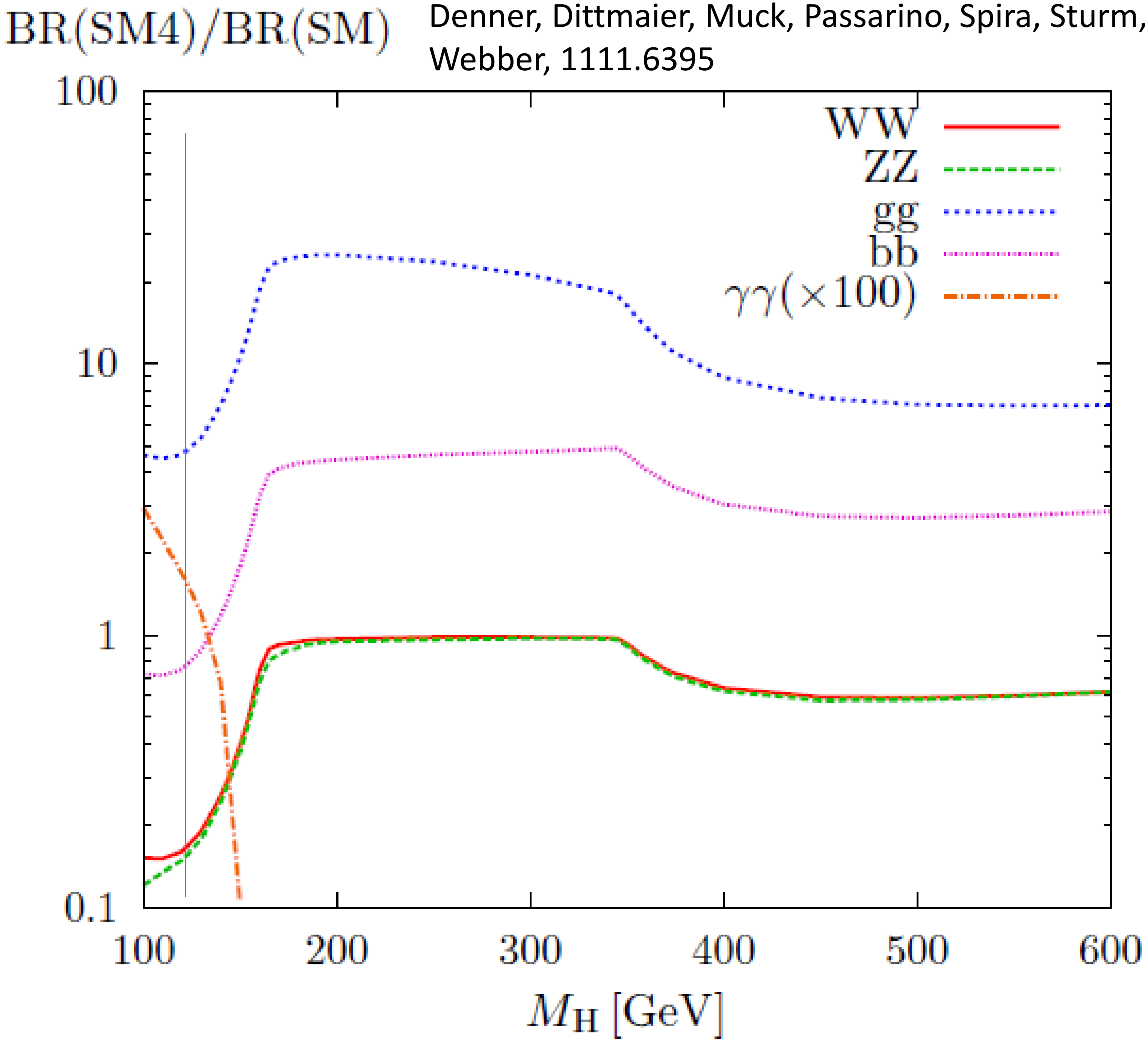
$$\Gamma_{h\to\gamma\gamma} \sim |W - Top - Top' - Bottom' - Tau' - 2\ \mathrm{Loop}|^2$$

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

- For fermion masses at the pertubative limit (600 GeV fermions), the cancelation between the LO and NLO correction is 90%.
- The cancellation can be as large as 99% for some masses.

$$R_{\gamma\gamma} \sim 1/100$$

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



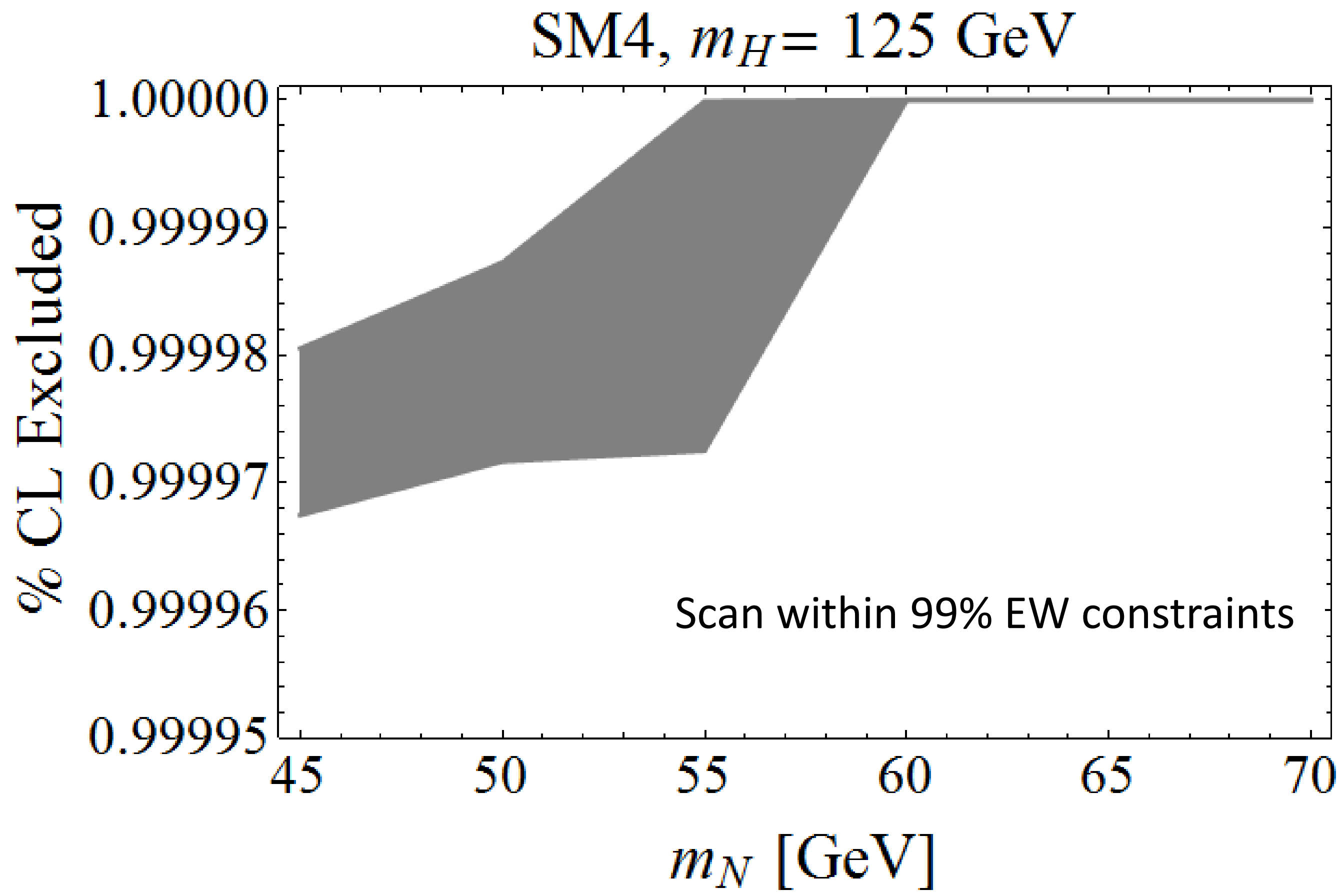
Will it work?

- $R_{VV} \sim \frac{\sigma_{gg} Br_{VV}}{\sigma_{gg} Br_{VV}|_{sm}} \sim 10\,\frac{\Gamma_{bb}}{\Gamma_{\mathrm{NN}}}$
- $R_{\gamma\gamma} \sim R_{\gamma\gamma,VBF} \sim \frac{\sigma_{gg} Br_{\gamma\gamma}}{\sigma_{gg} Br_{\gamma\gamma}|_{sm}} \sim .1\,\frac{\Gamma_{bb}}{\Gamma_{\mathrm{NN}}}$
- $R_{bb} \sim \frac{\sigma_{VH} Br_{bb}}{\sigma_{\sigma_{VH}} Br_{bb}|_{sm}} \sim \frac{\Gamma_{bb}}{\Gamma_{\mathrm{NN}}}$

Improving the constraints from WW and ZZ searches will make constraints from other searches stronger.

EW Constraints

Includes
$\gamma\gamma$
$VBF, \gamma\gamma$ (FB)
ZZ
$b\bar{b}$
WW
SM Excluded at 97%



G. D. Kribs, T. Plehn, M. Spannowsky, and T. M. Tait 0706.3718.

Includes

$\gamma\gamma$

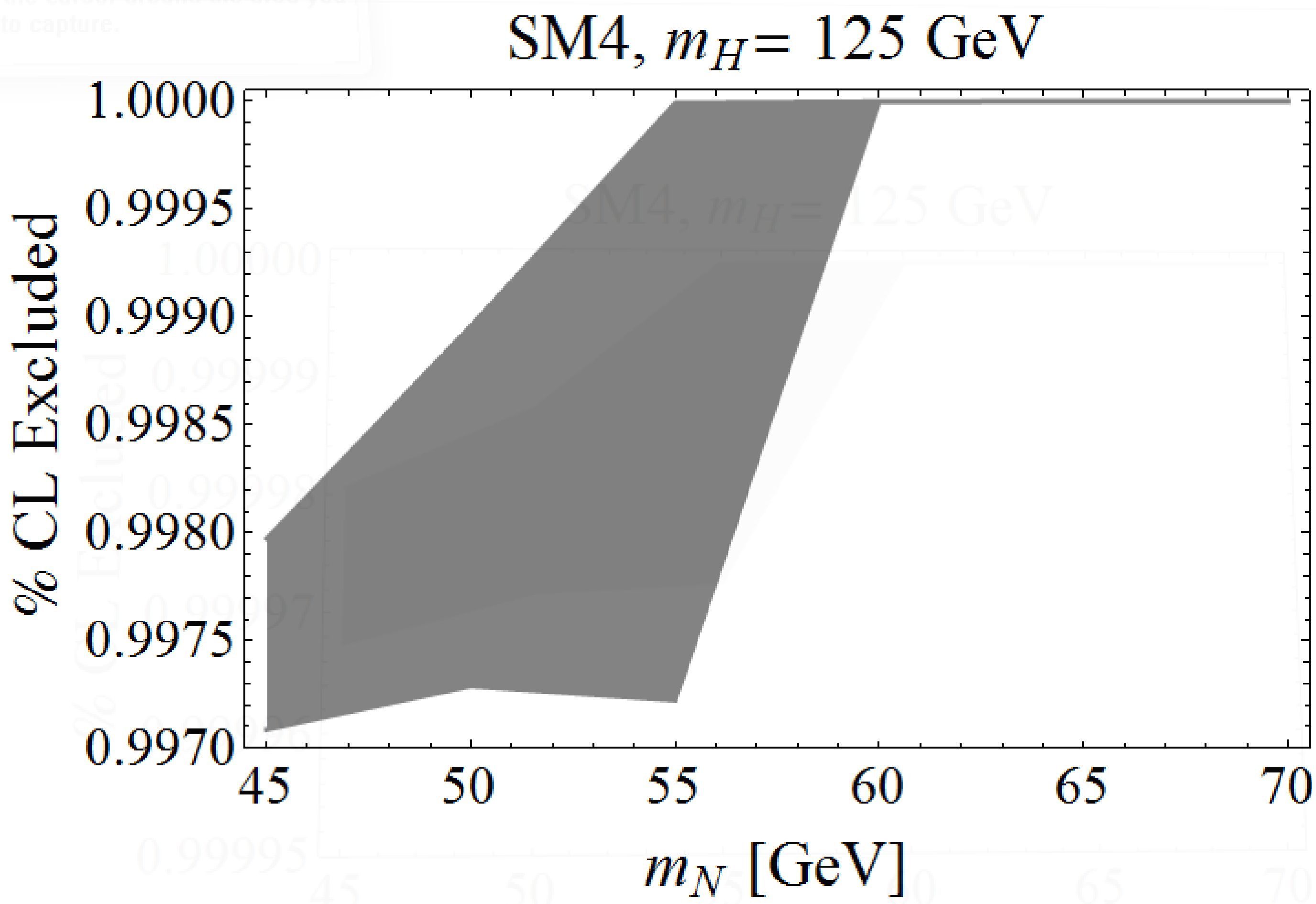
$VBF, \gamma\gamma$ (MVA)

ZZ

$b\bar{b}$

WW

SM Excluded at 86%



Robust?

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

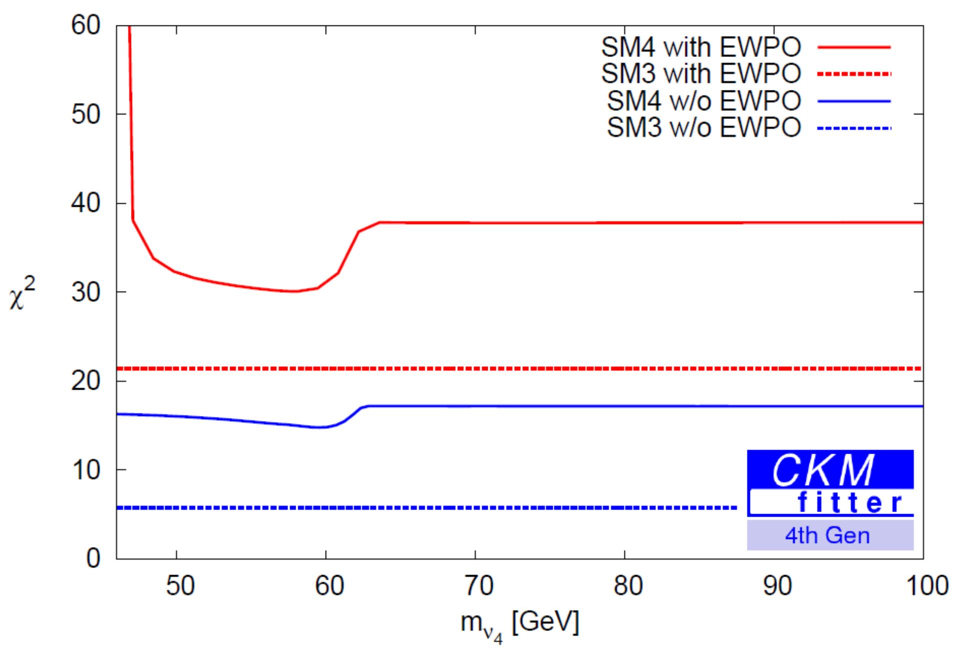
1%

- Care should be taken with the numerical codes as they only approximate the correction to $h \to \gamma\gamma$ at NLO to about 1% accuracy
  - Can result in an large inaccuracy in the actual width
- NNLO corrections may be large for the heavier masses.

- Weakest constraints are obtained when the fourth generation masses are lightest.
  - Smaller Yukawa couplings imply smaller corrections, and a small cancellation for $h \to \gamma\gamma$.
  - Also the range we expect the uncertainties to be lowest
    - NLO cancellation is less significant
    - NNLO corrections are smallest

More Constraints – Precision EW

- Combining with precision electroweak can lead to much stronger constraints
  - Instead of scanning over allowed parameter space from oblique parameters, including EWPO in the χ^2 would lead to much stronger constraints



Eberhardt, Herbert, Lacker, Lenz, Menzel, Nierste, Wiebusch [1204.3872]

Even more constraints – Direct Searches

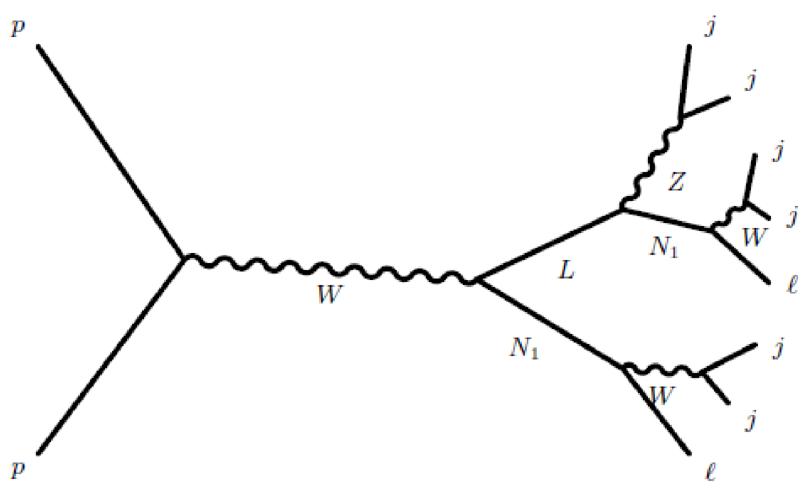
- Very strong, somewhat model dependent bounds on heavy quarks. They tend to push SM4 outside the perturbative regime.

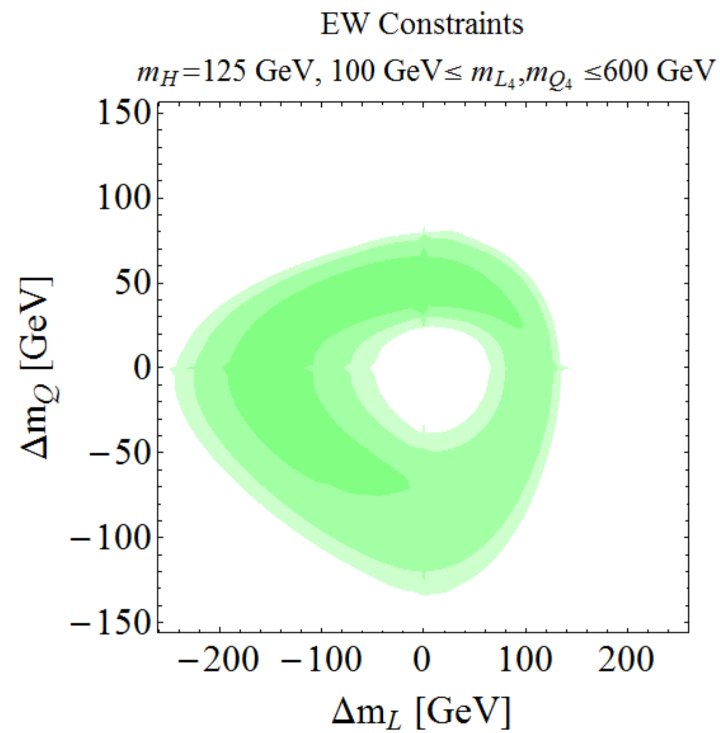
4^{th} generation quarks: Summary

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	$BB \to (Wt)(Wt) \to ljjjjjjX$	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

Direct Searches + EWP

- An LHC search at 7 TeV with 1 fb−1 of data can exclude fourth generation charged leptons with masses up to 250 GeV. Carpenter, Rajarman, Whiteson [1010.1011]
- S&T parameters constrain $m_{l'} - m_{N'} < 250$ GeV.
- Kill the 4th generation when combined with EWPO and Higgs rates.

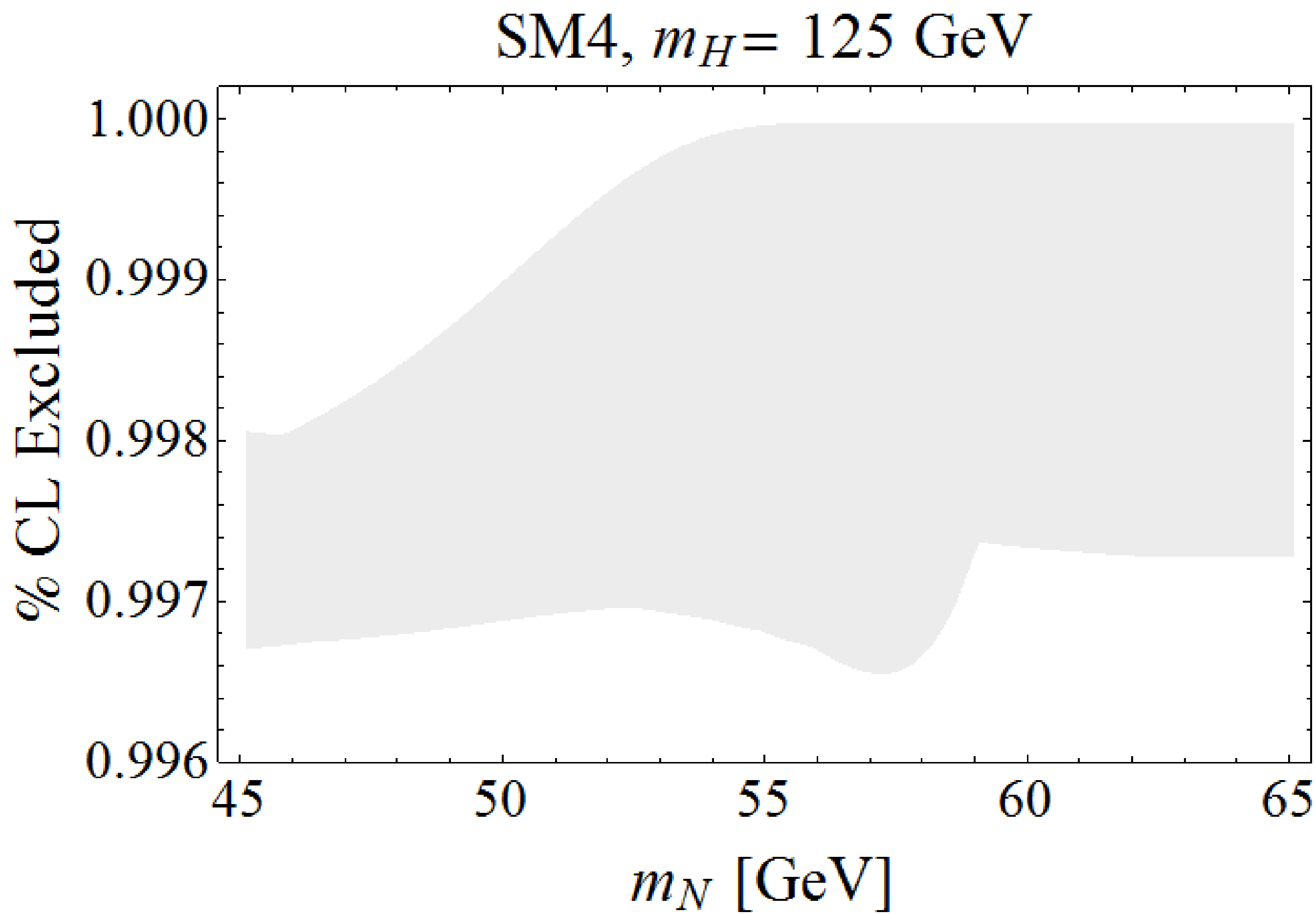


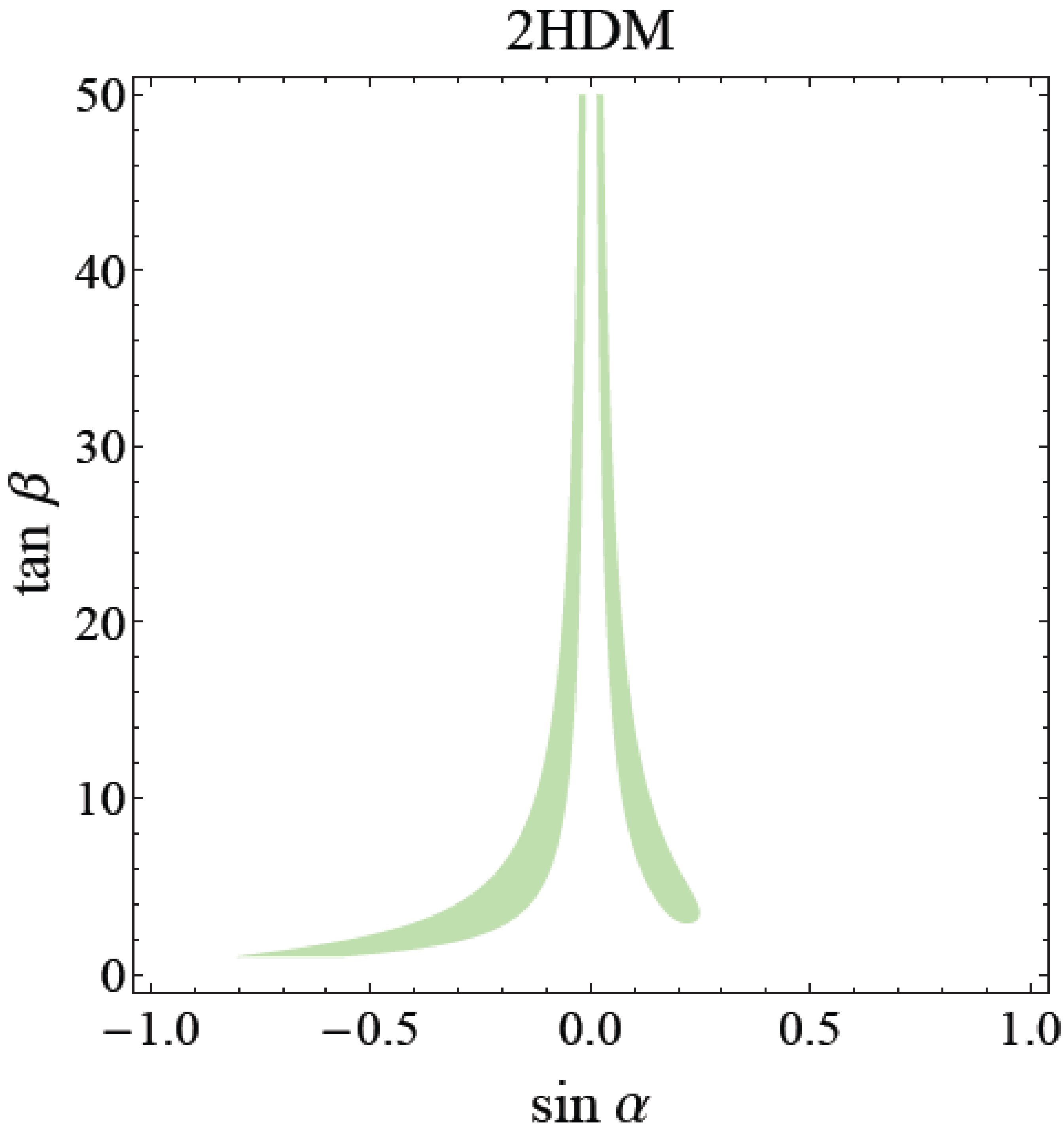


Summary

- 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
  - Has begun to rule out models

The End.


SM4, m_H= 125 GeV
% CL Excluded
1.000
0.999
0.998
0.997
0.996
45
50
55
60
65
m_N [GeV]



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