Interpreting The Higgs

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Based on 1207.1718 and 1202.3144
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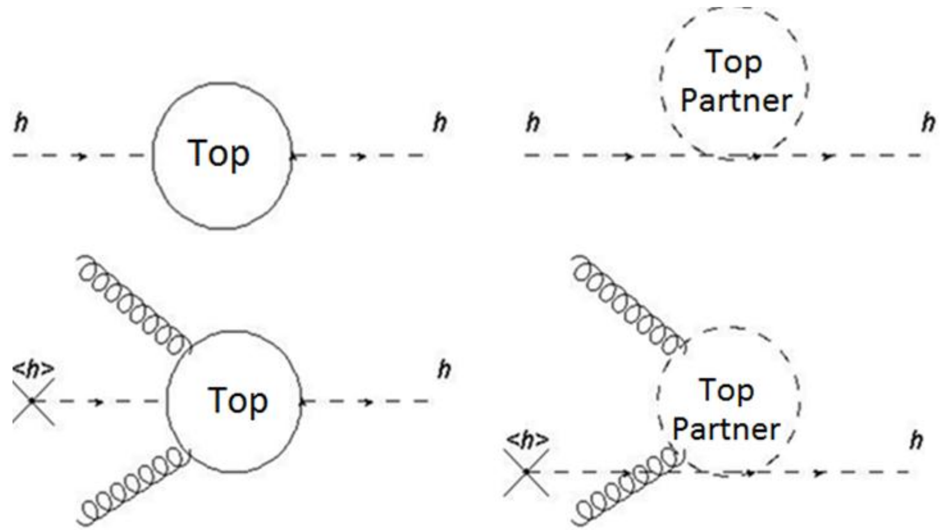
Quick Introduction

- Higgs is discovered

Naturalness and Higgs Rates

- If new physics exists, Higgs interactions are likely to be modified
- New particles introduced in models that resolve the fine tuning also enter in the gluon fusion and diphoton rates



- Higgs rates may be the best (only?) route to new physics!

Higgs Effective Theory

- Study more general Higgs Lagrangian
- Define effective Lagrangian at $\mu \sim m_h \sim 125$ GeV. Relevant couplings:

$$L = c_V \frac{2m_W^2}{v} W_\mu^+ W_\mu^- + c_V \frac{2m_W^2}{v} Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b} b - c_\tau \frac{m_b}{v} h\, \bar{\tau}\tau$$
$$+ c_g \frac{\alpha_s}{12\, \pi\, v} h\, G_{\mu\nu}^a G_{\mu\nu}^a + c_\gamma \frac{\alpha}{\pi\, v} h\, A_{\mu\nu} A_{\mu\nu} + c_\chi\, h \bar{\chi}\chi$$

- Few theoretical assumptions:
  - Higgs only couples to SM fields and an invisible particle.
  - Custodial symmetry fixes $c_W = c_Z = c_V$, so as to satisfy the experimental bounds on the T-parameter.
  - For simplicity also assume $c_b = c_\tau$
  - Higgs is a positive-parity scalar
- SM gives: $c_V = c_b \simeq c_g \simeq 1 \qquad c_\gamma \simeq 2/9 \qquad c_\chi = 0.$
- All couplings can be modified in BSM models

Higgs Widths

- All Higgs rates are a function of c_i

$$\frac{\Gamma_{h\to bb}}{\Gamma^{SM}_{h\to bb}} \simeq |c_b|^2 \qquad \frac{\Gamma_{h\to WW}}{\Gamma^{SM}_{h\to WW}} = \frac{\Gamma_{h\to ZZ}}{\Gamma^{SM}_{h\to ZZ}} \simeq |c_V|^2$$

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

$$\frac{\Gamma_{tot}}{\Gamma^{SM}_{tot}} \equiv |c_{tot}|^2$$

Where $\hat{c}_\gamma \approx c_\gamma - c_V$ takes into the W-contribution.

- These are approximate, but more precise relations are used.

Rates

- Assuming gluon fusion dominates the inclusive productions cross section ($R = \mu$, the signal strength):

$$R_{VV^*} \equiv \frac{\sigma_{pp\to h} Br_{h\to VV^*}}{\sigma^{SM}_{pp\to h} Br^{SM}_{h\to VV^*}} \simeq \left|\frac{c_g c_V}{c_{tot}}\right|^2$$

$$R_{\gamma\gamma} \equiv \frac{\sigma_{pp\to h} Br_{h\to\gamma\gamma}}{\sigma^{SM}_{pp\to h} Br^{SM}_{h\to\gamma\gamma}} \simeq \left|\frac{c_g\ \hat{c}_\gamma}{\hat{c}_{\gamma,SM} c_{tot}}\right|^2$$

$$R_{bb} \equiv \frac{\sigma_{pp\to Vh} Br_{h\to\bar{b}b}}{\sigma^{SM}_{pp\to Vh} Br^{SM}_{h\to\bar{b}b}} \simeq \left|\frac{c_b c_V}{c_{tot}}\right|^2$$

$$R_{\gamma\gamma jj} \equiv \frac{\sigma_{pp\to hjj} Br_{h\to\gamma\gamma}}{\sigma^{SM}_{pp\to hjj} Br^{SM}_{h\to\gamma\gamma}} \simeq \left(r_g |c_g|^2 + r_V |c_V|^2\right) \left|\frac{\hat{c}_\gamma}{\hat{c}_{\gamma,SM} c_{tot}}\right|^2$$

- These are approximate, but more precise relations are used. (All cross-sections included.)

EFT Goals

$$L = c_V \frac{2m_W^2}{v} W_\mu^+ W_\mu^- + c_V \frac{2m_W^2}{v} Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b}b - c_\tau \frac{m_b}{v} h\, \bar{\tau}\tau$$
$$+ c_g \frac{\alpha_s}{12\,\pi\, v} h\, G_{\mu\nu}^a G_{\mu\nu}^a + c_\gamma \frac{\alpha}{\pi\, v} h\, A_{\mu\nu} A_{\mu\nu} + c_\chi\, h \bar{\chi}\chi$$

- **Determine the region of the $c_i's$ favored by the LHC & Tevatron data.**
- **Is the data consistent with the SM Higgs?**
- **Is data favoring another scenario?**
- **Are the preferred regions consistent with natural theories?**

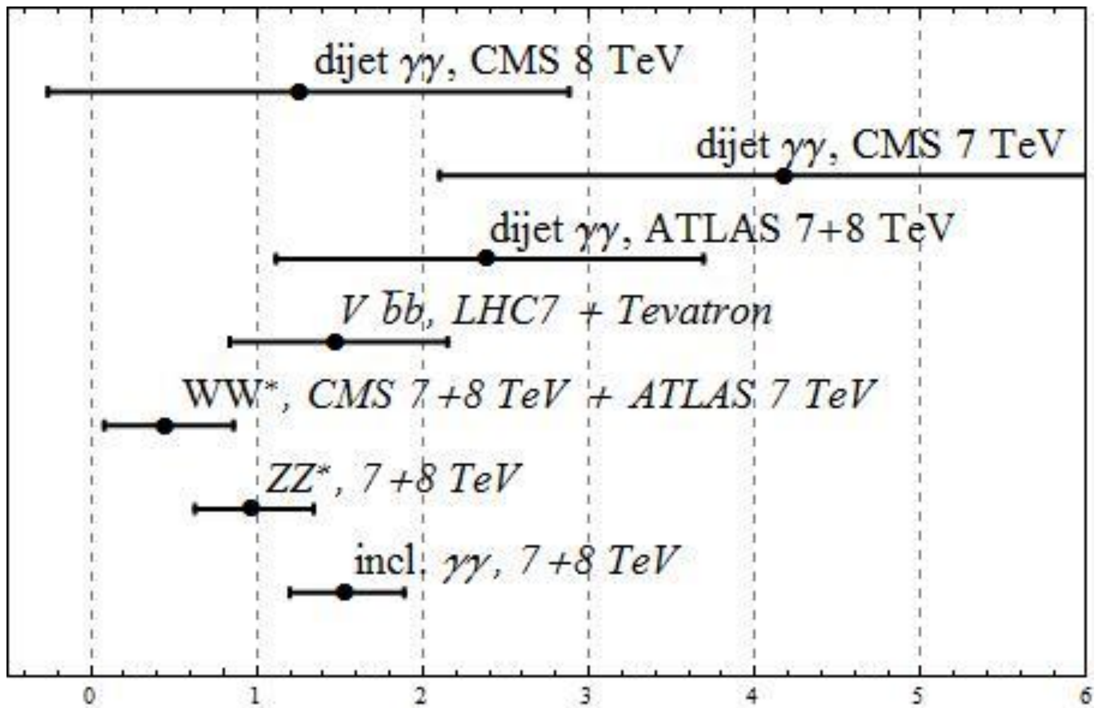
Similar Approaches

- A. Azatov, R. Contino and J. Galloway, JHEP 1204, 127 (2012) [arXiv:1202.3415 [hepph]] , arXiv:1206.3171 [hep-ph].
- P. Giardino, K. Kannike, M. Raidal and A. Strumia, JHEP 1206, 117 (2012) [arXiv:1203.4254 [hepph]], arXiv: 1207.1347
- J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, arXiv:1202.3697 [hepph]. , arXiv:1205.6790 [hep-ph], arXiv:1207.1717
- J. R. Espinosa, C. Grojean and M. Muehlleitner, arXiv:1202.1286 [hep-ph].
- J. Ellis and T. You, arXiv:1204.0464 [hep-ph], arXiv:1207.1693

Data

- Focus on the 5 most sensitive channels for $m_h = 125$ GeV.

$$h \to \gamma\gamma, \quad hjj \to \gamma\gamma jj, \quad h \to ZZ^* \to 4l, \quad h \to WW^* \to 4l, \quad Vh \to V\,\bar{b}b$$



- Always assume Gaussian statistics

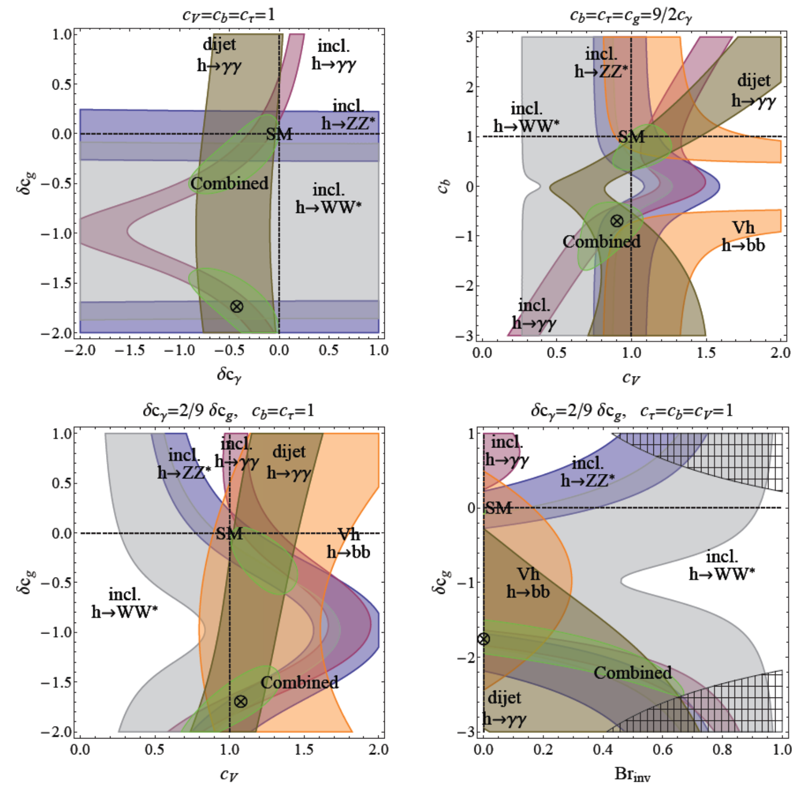
$$\chi^2 = \sum \left(\frac{R_i - \hat{R}_i}{\sigma_i}\right)^2 \qquad R = \frac{\sigma \cdot Br}{[\sigma \cdot Br]_{SM}}$$

Could be much better.

- Much can be improved with the full Likelihood functions
  - No correlations
  - Gaussian assumption is not always good.
  - Fixed Higgs mass
  - I have to digitize plots.

- Consider it warm-up exercise in preparation for better statistics.

2D Fits



$$\chi^2 = \sum \left(\frac{R_i - \hat{R}_i}{\sigma_i} \right)^2$$

$$R = \frac{\sigma \ \cdot Br}{[\sigma \cdot Br]_{SM}}$$

- Study the best-fit regions where only two of the above parameters can be freely varied, while the remaining ones are fixed to the SM values
- Representative of many BSM models
- Show 1σ bands for each of the 5 channels
- Combined region gives the 95% CL preferred region ($\Delta\chi^2 < 5.99$)
- Test against the Standard Model hypothesis, $\chi^2_{SM} - \chi^2_{min}$
- Very useful representation for theorists

New Charged and Colored Particles

- Only dimension-5 couplings may vary:

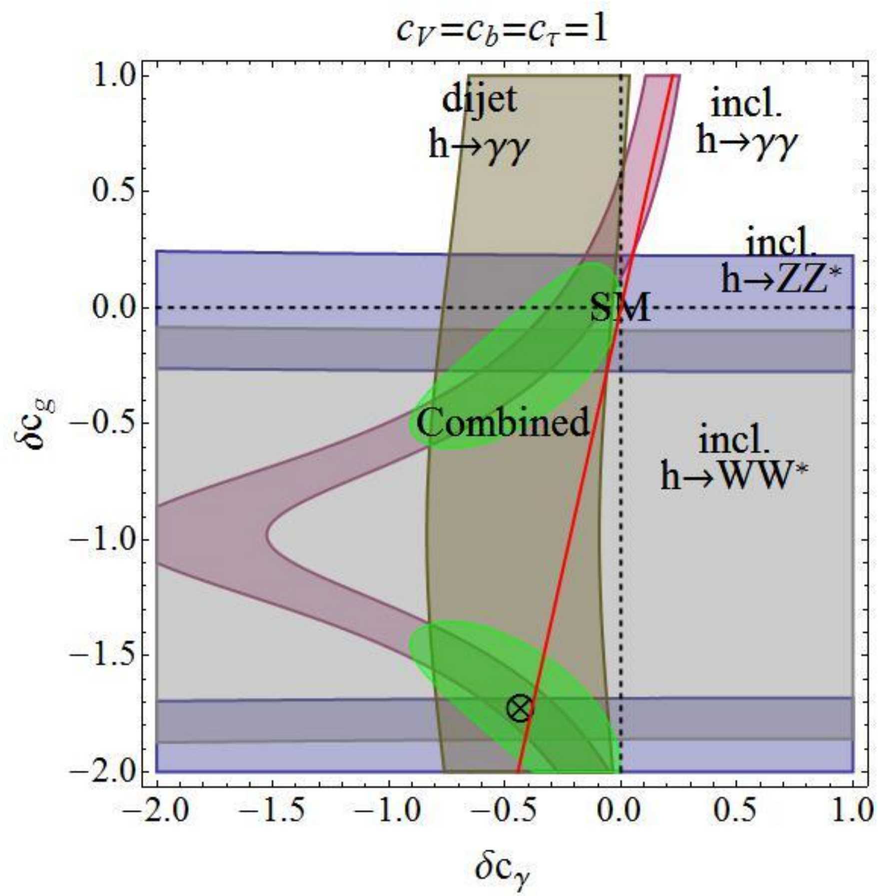
$$c_g \frac{\alpha_s}{12\,\pi\,v} h\, G^a_{\mu\nu} G^a_{\mu\nu} + c_\gamma \frac{\alpha}{\pi\,v} h\, A_{\mu\nu} A_{\mu\nu}$$

- Representative of models with additional charged and colored particles.
- Good fit can be obtained and improvements made over SM

$$\left(\chi^2_{SM} - \chi^2_{min}\right) = 6.1$$

- SM point at 95% CL border

- Top Partner Models give excellent fits.
  - Models where only particles with the same charge and color as the top contribute (only 1 dof)
  - $\delta c_\gamma = \frac{2}{9}\delta c_g$ (red line)



Combined: Region of $\chi^2 - \chi^2_{SM} \le 5.99$

Invisible Higgs

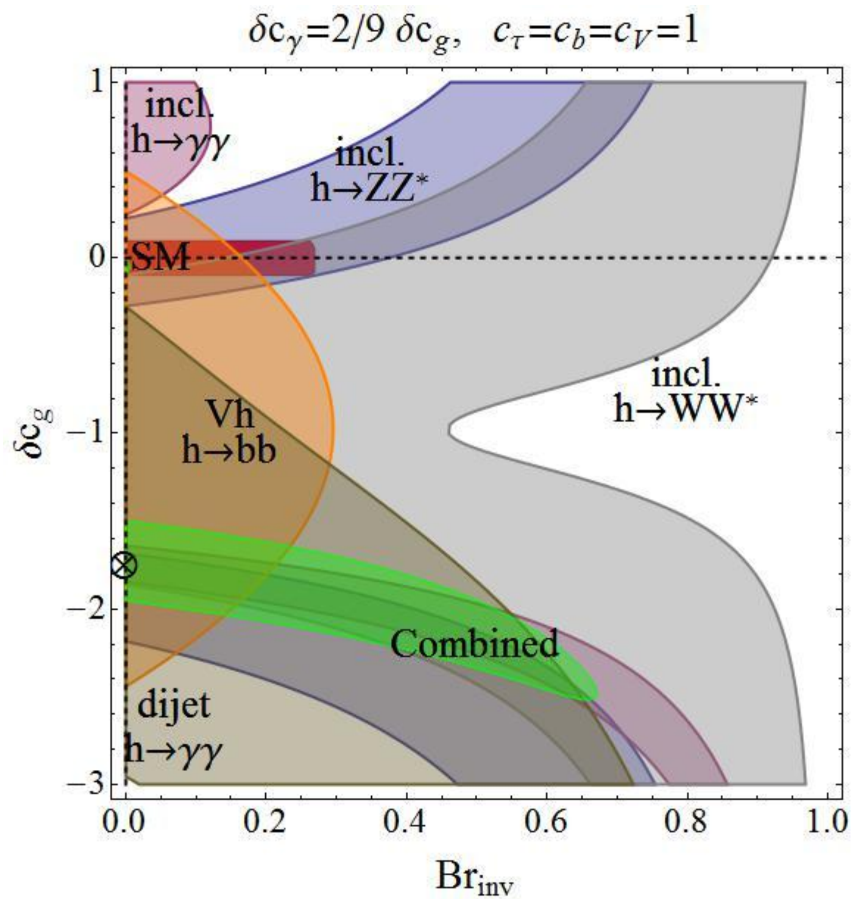
- Dimension-5 couplings may vary according to top partner relationship:

$$c_g \frac{\alpha_s}{12\,\pi\,v} h\, G^a_{\mu\nu} G^a_{\mu\nu} + \frac{2c_g}{9} \frac{\alpha}{\pi\,v} h\, A_{\mu\nu} A_{\mu\nu}$$

Plus additional invisible mode

$$c_\chi\, h \bar{\chi} \chi$$

- Large invisible rate allowed if c_γ (the di-photon rate) is enhanced.
- Fit is only improved because of the inclusion of a top-partner
- If just invisible mode (1 dof), fits are not improved over the SM (Red region)



$$(\chi^2_{SM} - \chi^2_{min}) = 0 \qquad \text{Br}_{\text{inv}} < 0.27$$

For more on invisible Higgs: J. R. Espinosa, M. Muhlleitner, C. Grojean and M. Trott, arXiv:1205.6790, arXiv:1207.1717
For Collider constraints see: A. Djouadi, A. Falkowski, Y. Mambrini and J. Quevillon, arXiv:1205.3169 [hep-ph].

Another Parameterization

- Parameterizes top-partner with Higgs mixing

$$c_g \frac{\alpha_s}{12\,\pi\,v} h\, G^a_{\mu\nu} G^a_{\mu\nu} + \frac{2c_g}{9} \frac{\alpha}{\pi\,v} h\, A_{\mu\nu} A_{\mu\nu}$$

$$c_b = c_v = c_\tau \sim \cos\theta$$

- Fits much improved over the SM

$$\left(\chi^2_{SM} - \chi^2_{min}\right) = 6.5$$

  - SM outside 95% CL Region

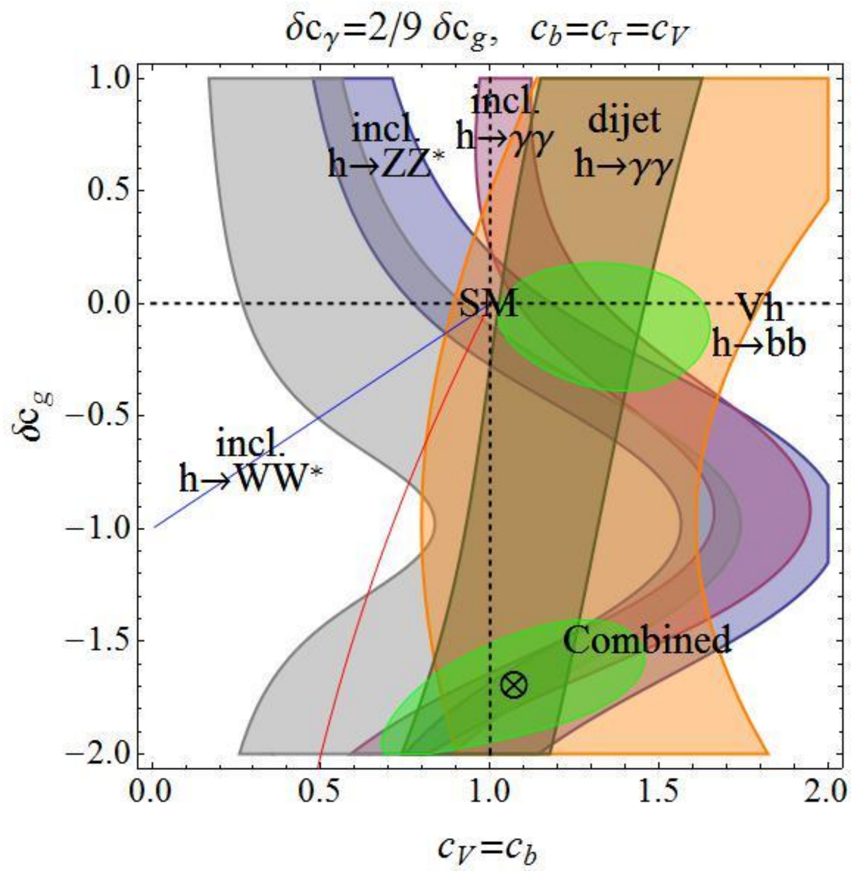
- Examples include Little Higgs models (only 1 dof)

$$c_V = c_b = \sqrt{1 - \xi/2}$$

Twin Higgs: $\delta c_g = \sqrt{1 - \xi/2}$

Simplest Higgs: $\delta c_g = (1 - \xi)/\sqrt{1 - \xi/2}$

No improvement over SM, for Twins Higgs or Simplest Higgs models.
$\chi^2_{SM} \leq \chi^2$



The Top Partner

- Models where only particles with the same charge and color as the top contribute (only 1 dof)
- Well motivated by the hierarchy problem.
- Preserves the relationship: $c_\gamma = \frac{2}{9} c_g$
- Model can have many parameters, but only 1 combination affects the fits.
- Schematically:

Interference - top is 20% of the W contribution

$$\Gamma_{gg} \sim |top|^2 \qquad \Gamma_{\gamma\gamma} \sim |-W + top|^2$$

$$\Gamma_{gg} \sim |top \pm top'|^2 \qquad \Gamma_{\gamma\gamma} \sim |-W + top \pm top'|^2$$

Top Partners

- Top Partner contribution significantly improves the fits when its contribution is almost twice the SM top contribution but opposite in sign.

$\Gamma_{gg} \sim |top \pm top'|^2 \qquad \Gamma_{\gamma\gamma} \sim |-W + top \pm top'|^2$

$\Gamma_{gg} \sim |top - 1.8\ top|^2 \qquad \Gamma_{\gamma\gamma} \sim |-W + top - 1.8\ top|^2$

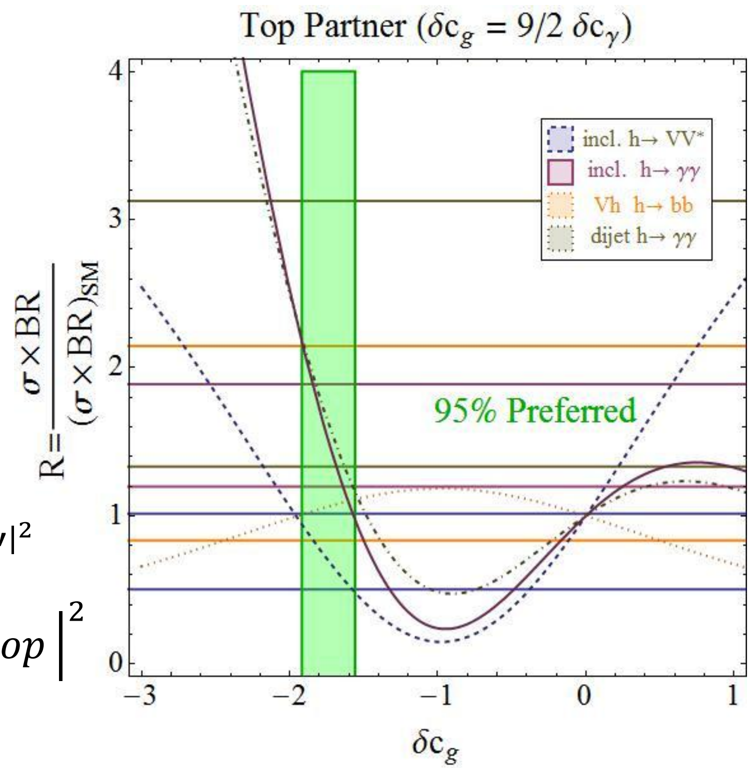
- Gluon fusion remains roughly constant –

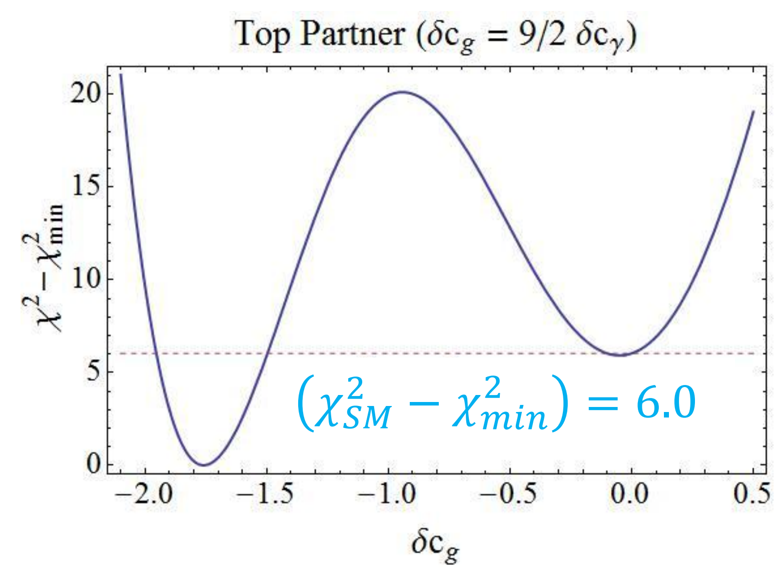
$h \rightarrow ZZ, WW, bb$ are unchanged

$h \rightarrow \gamma\gamma$ increases

- Dropping the top partner assumption $\delta c_\gamma = 2/9\ \delta c_g$ does not improve the fits.
- No improvement over SM if $\delta c_g > 0$
- Generally the sign is related to naturalness:

I. Low, R. Rattazzi and A. Vichi,.





Fermion Top Partner

- Consider simplified model with a single fermion top partner.

$$L = -c_f \frac{m_f}{v} h \, \bar{f} f$$

$$\delta c_g = 9/2 \delta c_\gamma = c_f A_f (m_h^2/4m_f^2) \qquad A_f \sim 1$$

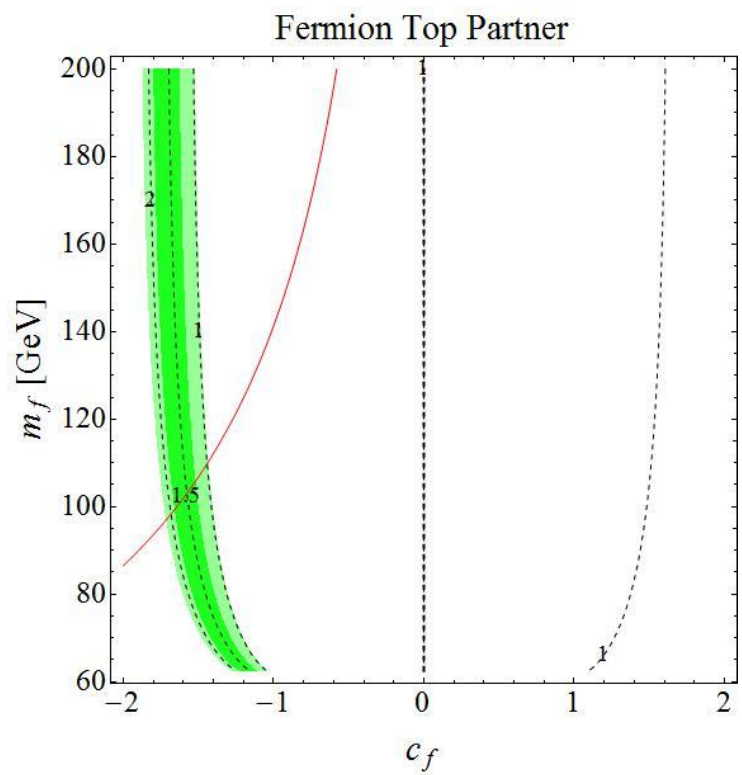
- Quadratic divergence cancelled for

$$c_f m_f = -2\, m_t^2/[m_f + \sqrt{(2m_t^2 + m_f^2)}]$$

- Can cancel the quadratic divergence and improve the fits if

$$95 \text{ GeV} < m_f < 115 \text{ GeV}$$

- Cannot get its mass entirely from EWSB (chiral top partners disfavored)



Scalar Top Partner

- Consider simplified model with a single scalar top partner.

$$L = -c_s \frac{2\,m_s}{v} h\, S^* S$$

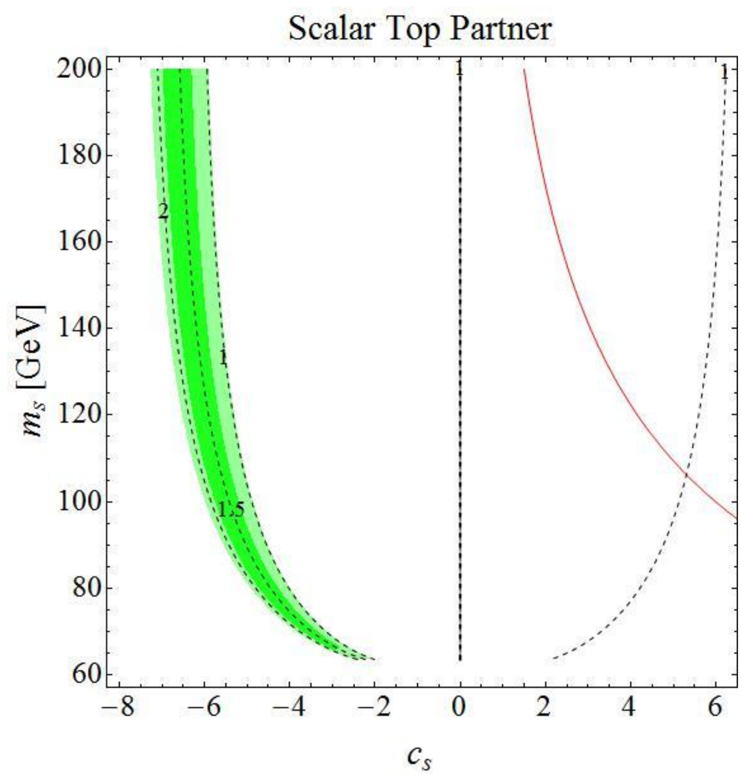
$$\delta c_g = 9/2\delta c_\gamma = \frac{c_s}{4} A_s(m_h^2/4m_f^2) \qquad A_s \sim 1$$

- Quadratic divergence cancelled for

$$c_s = 2m_t^2/m_s^2$$

- Cannot simultaneously improve the fits and cancel the quadratic divergence, since

$$\delta c_g = 9/2\delta c_\gamma \geq 0$$



Two Scalars - SUSY

- Stop sector of the MSSM (neglecting sub-leading D-terms)

$$L = |\tilde{t}_L|^2(m_L^2 + y_t^2|h|^2) + |\tilde{t}_R|^2(m_R^2 + y_t^2|h|^2) + y_t X_t h t_L t_R + h.c.$$

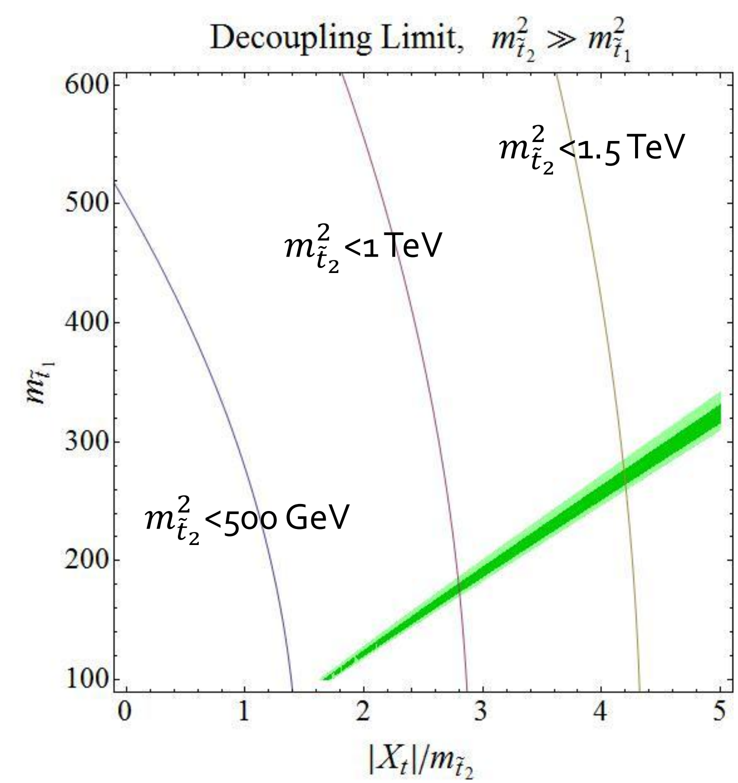
- Quadratic divergence cancelled.
- Consider decoupling limit, $m_A \gg m_h$.
  - Non-decoupling limit only makes the fits worse.
- Stops mix $\quad m_t X_t = \frac{1}{2}\left(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2\right)\sin^2 2\theta_t$
- Mixing allows for negative δc_g

$$\delta c_g = 9/2\,\delta c_\gamma = \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2}{m_{\tilde{t}_1}^2}\frac{|X_t|^2}{m_{\tilde{t}_2}^2}\right)$$

- The two states must have large separation

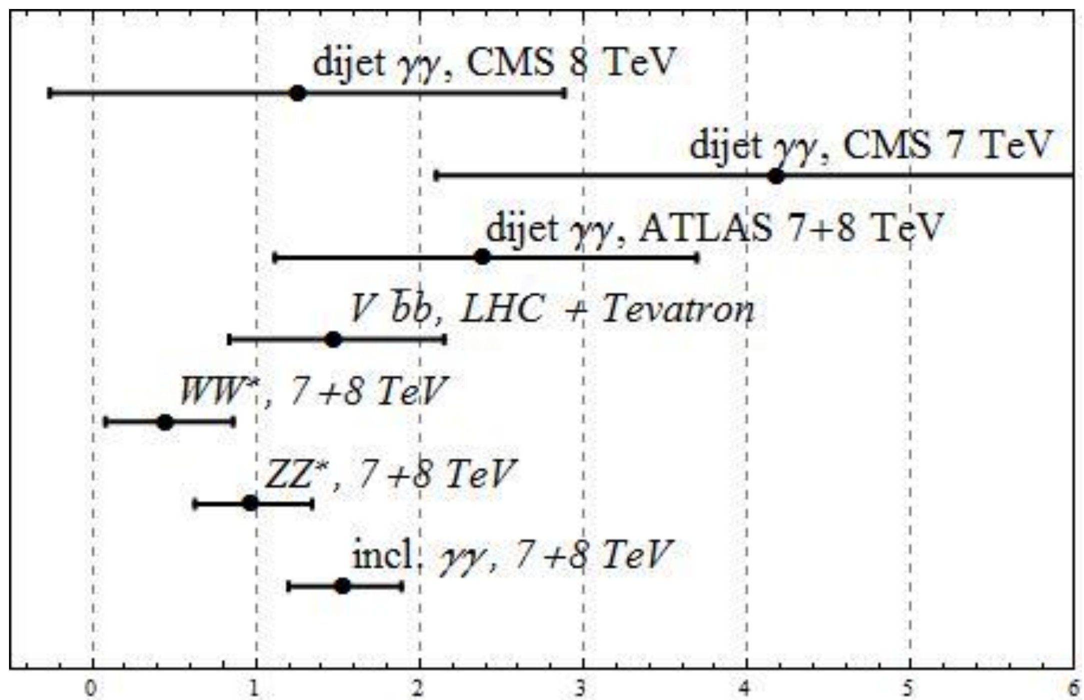
$$X_t/m_{\tilde{t}_2} < \left(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2\right)/\left(2 m_t m_{\tilde{t}_2}\right)$$

- Can you get the right Higgs mass from the combination of very large mixing, large mass separation, but one light stop?



Models of Enhanced Diphoton Rates

Data shows increased $h \to \gamma\gamma$



Hint for new charged particles?

See also M. Carena, I. Low, C. Wagner 1206.1082

New W′ Partner

- Consider simplified model with a W′

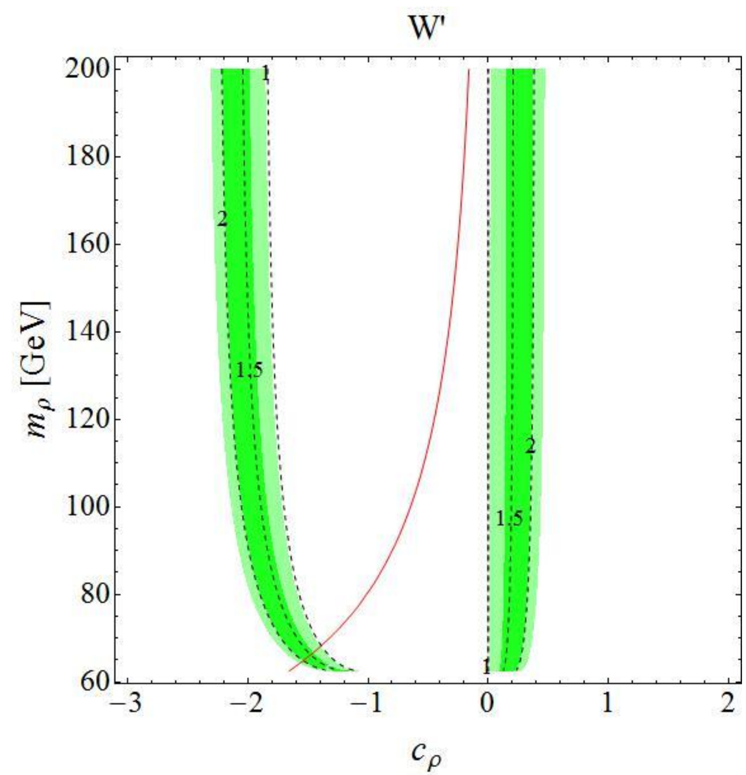
$$L = +c_\rho \frac{2m_\rho^2}{v} h \, \rho_\mu^* \rho_\mu$$

$$\delta c_g = 0 \qquad \delta c_\gamma = -\frac{7}{8} c_\rho A_\rho (m_h^2/4m_\rho^2) \qquad A_\rho \sim 1$$

- Two best fit regions for W′

- Much improved fit over SM

$$\chi^2_{SM} - \chi^2_{min} = 4.3$$



Doublet-Singlet Model

- Higgs doublet mixes with a singlet, which couples to additional charged vector-like particles.

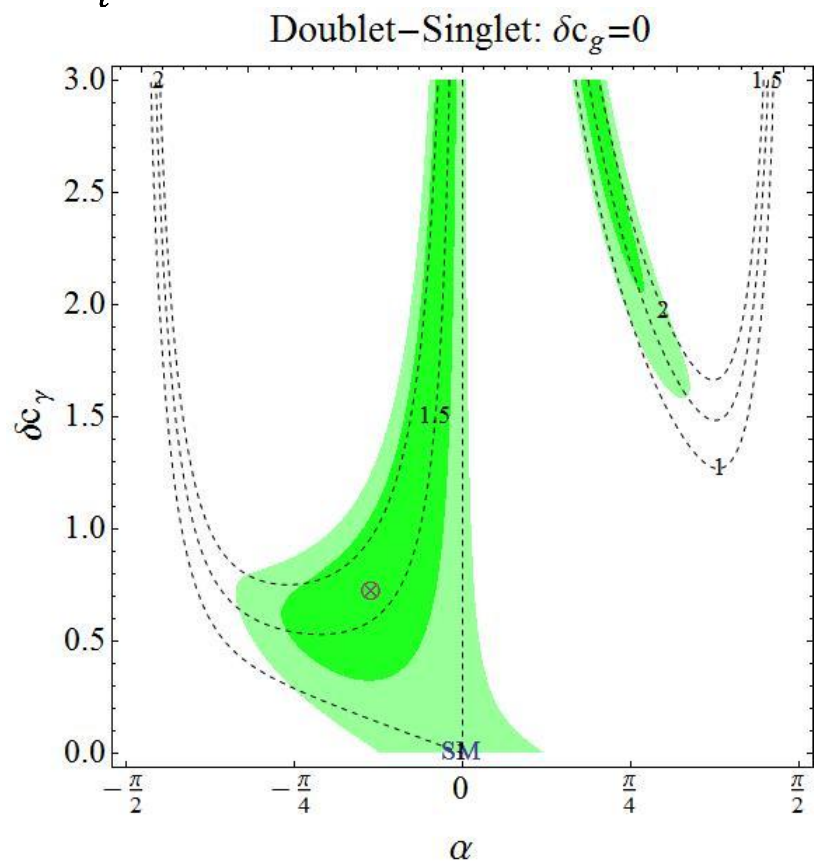
$$L = -\frac{1}{2} m_\phi^2 \phi^2 - \kappa\phi |H|^2 - \sum_i M_i \left(1 + \frac{\lambda_i}{v}\phi\right) \bar{\psi}\psi$$

- Higgs is a combination Doublet and Singlet

$$h = H \cos\alpha + \phi \sin\alpha$$

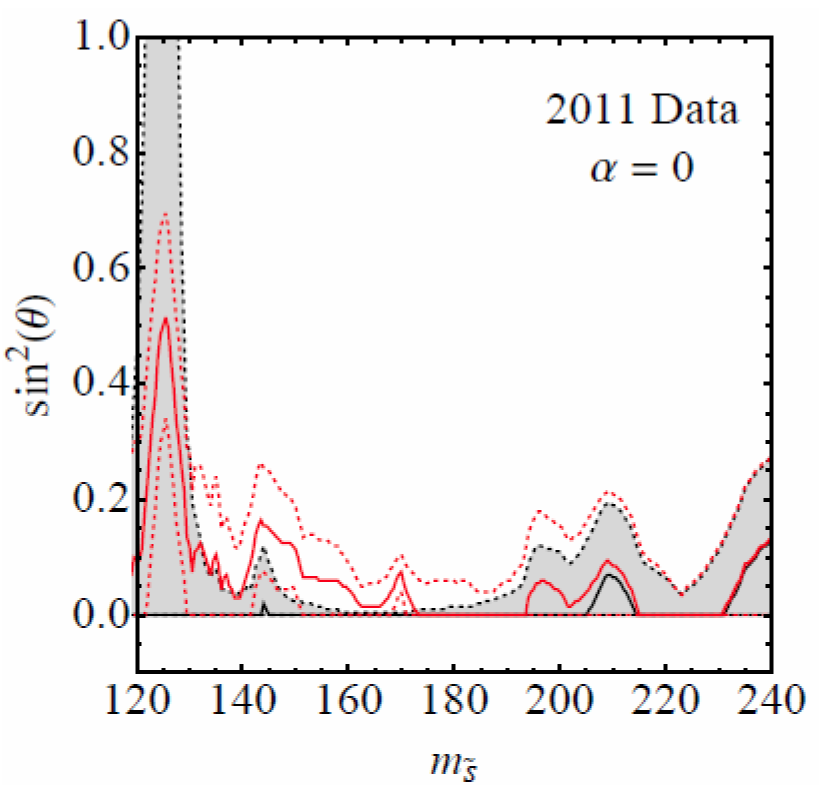
- Sign contribution to c_γ can be negative since the mass is not coming from EWSB.
- Better than just coupling the Higgs directly to leptons

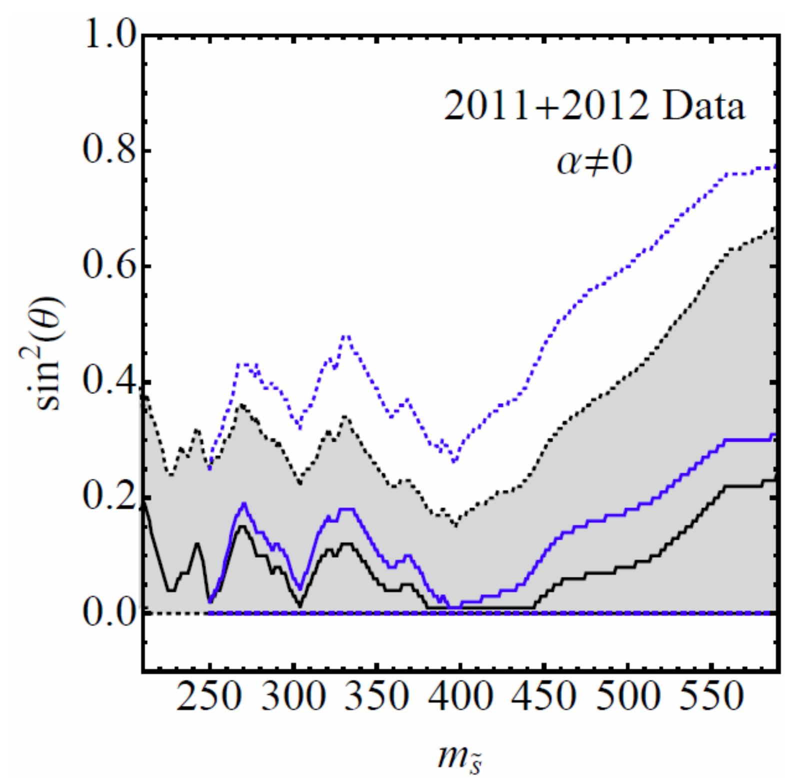
$$c_\gamma = c_{\gamma,SM} \cos\alpha + \delta c_\gamma \sin\alpha$$
$$\delta c_\gamma = \Sigma_i \lambda_i \tfrac{1}{6} N_i Q_i^2 A_f(\tau_i)$$



A Social Higgs – Bertolini & McCullough

- Predicts an additional resonances in the other channels, in particular the diphoton channel.





Type II Two Higgs Doublet Model

- 2 Higgs fields, one Up and one Down type Higgs

$$h = \cos\alpha\, Re\,(H_u^0) - \sin\alpha\, Re\,(H_d^0)$$

$$\tan\beta = v_u/v_d$$

- For $\tan\beta \geq 1$ the model always does worse than SM.

  Best fit corresponds to decoupling limit

- For $\tan\beta \leq\ 1$ there can be significant improvements when

$$\tan\beta \simeq 0 \quad \alpha \simeq \frac{\pi}{2}$$

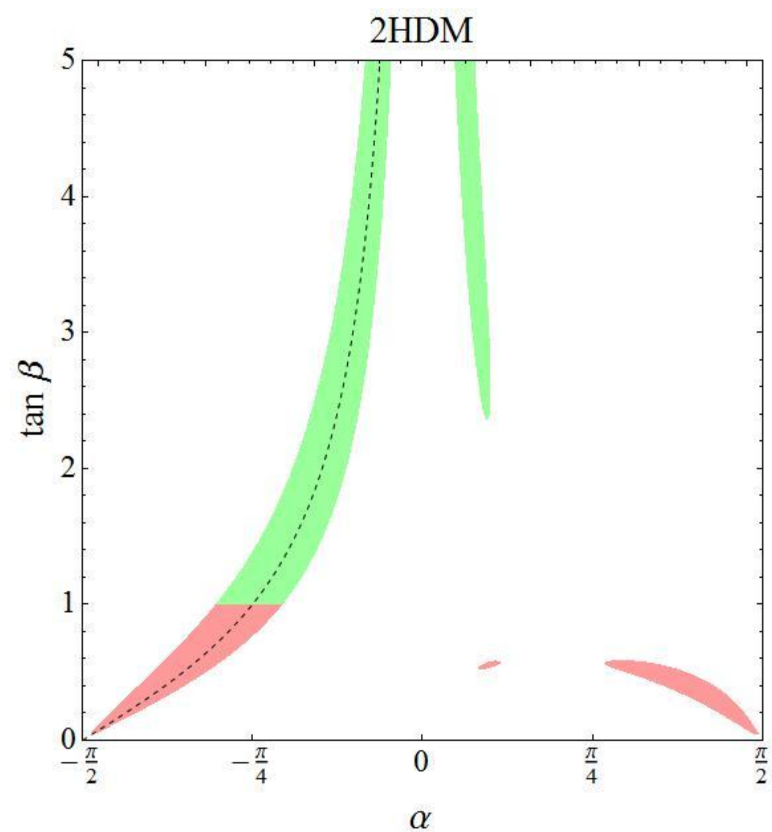
- Couplings are reduced, but the W and top quark can be made to constructively interfere

  sick limit – landau poles

$$c_V = \sin(\beta - \alpha)$$

$$c_b = -\frac{\sin\alpha}{\cos\beta}$$

$$c_g = 9/2\ c_\gamma = \frac{\cos\alpha}{\sin\beta}$$



Cynical View

- Higgs is half full of BSM? or
- Higgs is half full of SM?

New physics should cancel the quadratic divergence, so the new particles must be light

We observe SM-like rates, so the new particles must be heavy

Summary

- Measuring Higgs coupling may soon give us strong hints favoring or disfavoring particular models beyond the Standard Model

$$L = c_V \frac{2m_W^2}{v} W_\mu^+ W_\mu^- + c_V \frac{2m_W^2}{v} Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b} b - c_\tau \frac{m_b}{v} h\, \bar{\tau}\tau$$
$$+ c_g \frac{\alpha_s}{12\, \pi\, v} h\, G_{\mu\nu}^a G_{\mu\nu}^a + c_\gamma \frac{\alpha}{\pi\, v} h\, A_{\mu\nu} A\_\mu\nu + c_\chi\, h \bar{\chi}\chi$$

- Effective theory approach provides a robust framework to study this problem