Interpreting Higgs results

Adam Falkowski
LPT Orsay

Planck'12 Warszawa, 28 Maja 2012

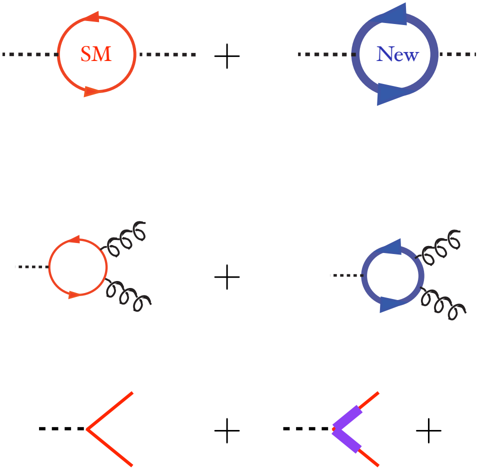
Carmi,AA,Kuflik,Volansky [1202.3144]
AA,Rychkov,Urbano [1202.1532]
Djouadi,AA,Mambrini,Quevillon [1205.3169]
+ *oven fresh unpublished*

Outline

Motivaton, in case you need it...

- The SM Higgs with mass $m_h \ll 2m_W$ has many decay channels that are potentially observable at the LHC and Tevatron ($H \to ZZ^*$, $H \to \gamma\gamma$, $H \to b\bar{b}$ $H \to WW^*$, $H \to \tau^+\tau^-$).
- Also different production channels can be isolated (gluon fusion, vector boson fusion, W/Z and $t\bar{t}$ associated production)
- Rich Higgs physics available in near future
- If new physics exists, Higgs interactions likely to be modified
- If new physics restores naturalness, Higgs interactions are necessarily modified
- Measuring Higgs rates at the LHC may be the shortest route to new physics!

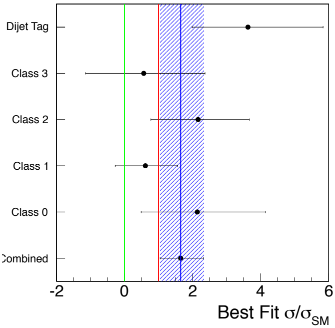
Hierarchy problem and Higgs physics

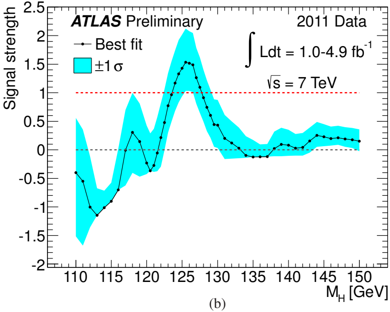


stolen from R. Rattazzi

Higgs

Observations

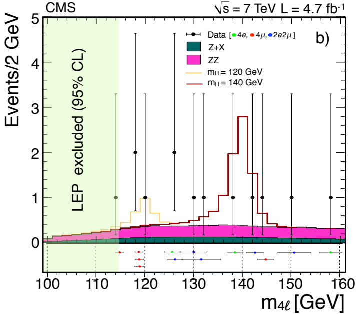


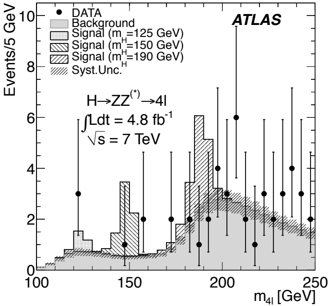


(b)

- Significant background, but great mass resolution
- Both ATLAS and CMS observe an excess near $m_h \sim 125$ GeV, ATLAS centered at 126 and CMS centered at 125
- In both case the best fit cross section at the peak exceeds the SM value, though the latter is well within uncertainties
- CMS also observes an excess in inclusive $\gamma\gamma jj$ channel dominated by VBF production mode, corresponding to cross section well exceeding the SM one (though, again, uncertainties are still large)

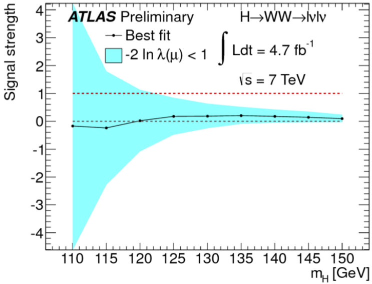
$H \to ZZ^* \to 4l$





- Very low background, great mass resolution
- ATLAS has 3 events at $m_{4l} \approx 124$ GeV
- CMS has 2 events at $m_{4l} \approx 126$ GeV

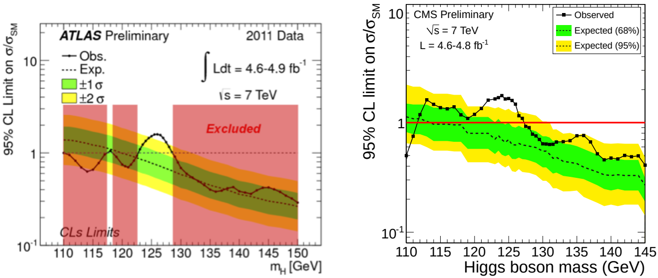
$H \to WW^* \to 2l2\nu$



		Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	Z/γ^* + 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

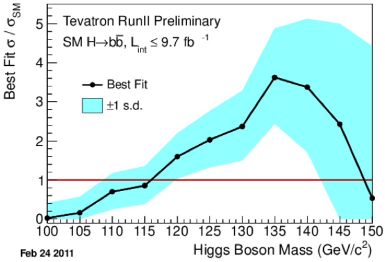
- Significant background, poor mass resolution, better for exclusion than discovery
- No clear excess here, which begins to feel weird
- Bad luck, background misestimation, or something interesting going on?

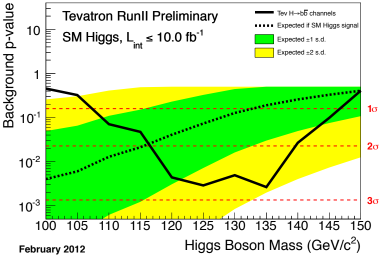
Exclusion limits



- Low mass range excluded by Tevatron and LHC except for 122-127 GeV range
- Even lower mass range excluded by LEP,
- High mass range excluded by LHC, or highly disfavored by EWPT
- Within the SM, no more "elsewhere"!

$VH \to bb$ at Tevatron





- Points to somewhat enhanced rate in *VH* production channel, the heavier Higgs, the larger cross section boost is needed
- Doesn't strongly favor any mass between 120 and 135 GeV

Experimentalists:

Not enough data to conclude the existence or non-existence of the Higgs boson

Theorists:

Come on... it's 125 GeV

This talk:

Assuming Higgs exists at 125 GeV
what's next?

Next

Is it the SM Higgs?

Higgs

Theory

Higgs effective theory

Define effective Higgs Lagrangian at $\mu \approx m_h \sim 125 GeV$. Couplings relevant for current LHC data

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

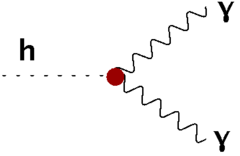
- Few theoretical prejudices here:
  - Assuming Higgs couples to SM fields only
  - Custodialy symmetry fixing $c_W = c_Z \equiv c_V$ (otherwise quadratically divergent contributions ΔT)
  - Scalar (rather than pseudoscalar) interactions only
- Top already integrated out, contributing to c_g and c_γ
- SM predicts $1 = c_V = c_b \approx c_g$ and $c_\gamma = 2/9$
- Any of the couplings can be modified in specific scenarios beyond the SM
- All LHC Higgs rates can be easily expressed as functions of the c_i couplings

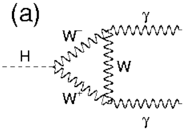
Higgs Widths

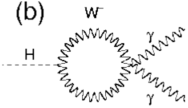
Higgs decay widths relative to SM modified approximately as,

$$
\begin{aligned}
\frac{\Gamma(h \to b\bar{b})}{\Gamma_{SM}(h \to b\bar{b})} &\simeq |c_b|^2 \\
\frac{\Gamma(h \to WW^*)}{\Gamma_{SM}(h \to WW^*)} = \frac{\Gamma(h \to ZZ^*)}{\Gamma_{SM}(h \to ZZ^*)} &\simeq |c_V|^2 \\
\frac{\Gamma(h \to gg)}{\Gamma_{SM}(h \to gg)} &\simeq |c_g|^2 \\
\frac{\Gamma(h \to \gamma\gamma)}{\Gamma_{SM}(h \to \gamma\gamma)} &\simeq \left| \frac{\hat{c}_\gamma}{\hat{c}_{\gamma,SM}} \right|^2
\end{aligned}
\qquad (1)
$$

where, taking into account W loop and assuming $m_h \approx 125$ GeV , $\hat{c}_\gamma \approx c_\gamma - c_V$, and $\hat{c}_{\gamma,SM} \approx -0.8$







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

$$\frac{\Gamma_{tot}}{\Gamma_{tot,\mathrm{SM}}} \approx 0.61 c_b^2 + 0.24 c_V^2 + 0.09 c_g^2 + 0.06 c_\tau^2 \equiv c_{tot}^2$$

Assuming $H \to bb$ dominates Higgs widths

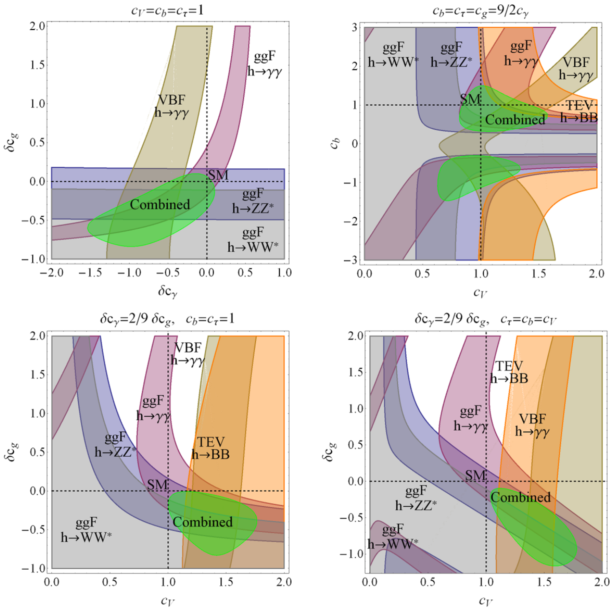
$$\begin{aligned}
R_{VV^*} &\equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to ZZ^*)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to ZZ^*)} \simeq \left|\frac{c_g c_V}{c_{tot}}\right|^2 , \\
R_{\gamma\gamma} &\equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to \gamma\gamma)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h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

Effective Theory Interpretation

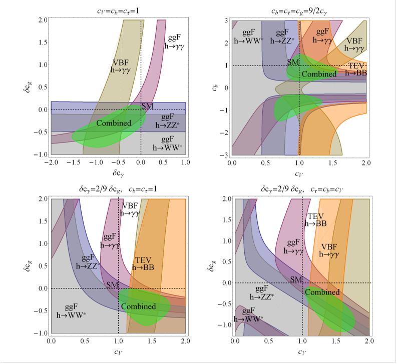
$$
\begin{aligned}
\mathcal{L}_{eff} \quad = \quad & c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu - c_b \frac{m_b}{v} h\, \bar{b} b - c_b \frac{m_\tau}{v} h\, \bar{\tau}\tau \\
& + c_g \frac{\alpha_s}{12\pi v} h\, G_{\mu\nu}^a G_{\mu\nu}^a + c_\gamma \frac{\alpha}{\pi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

- Carmi+ [1202.3144] : determine the region of effective theory parameter space favored by current Higgs data
- Question whether the current LHC data are consistent with the SM Higgs
- Question whether they favor or disfavor any particular BSM scenario
- Of course at this stage one cannot make very strong statements about Higgs couplimgs (some of you don't even think Higgs has been discovered)
- Consider it warm-up exercise in preparation for better statistics
- Recently similar approach in Azatov+ [1202.3415] , Espinosa+ [1202.3697] , Giardino+ [1203.4254] , Rauch [1203.6826] , Ellis,You [1204.0464] , Farina+ [1205.0011] , Klute+ [1205.2699]

Fits assuming $m_h = 125$ GeV

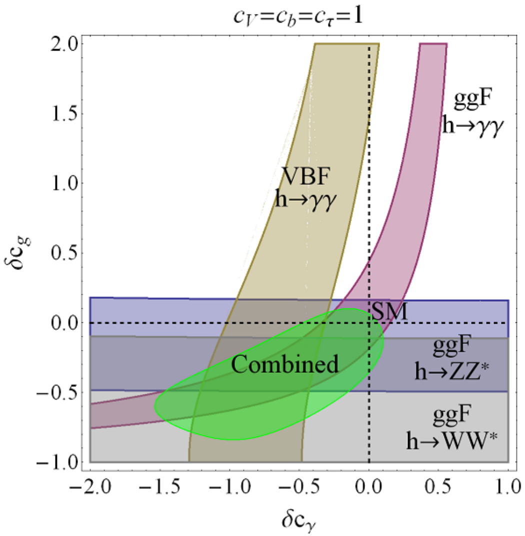


Fits assuming $m_h = 125$ GeV



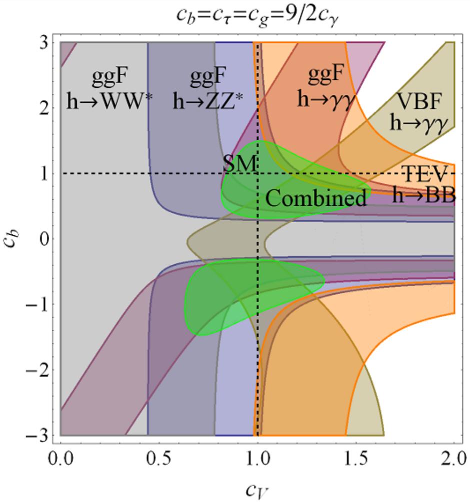
- We consider 2D planes in the parameter space
- Fixing all but 2 parameters (not marginalizing over) and fitting the remaing 2
- 1 sigma bands for 5 most sensitive search channels shown
- Combined $= \Delta\chi^2 < 4.61$, corresponding to 90% CL

Fits assuming $m_h = 125\,GeV$



- Only dimension-5 Higgs couplings allowed to vary (motivated if new physics enters only via loops)
- On this plane Tevatron never within 1 sigma band

Fits assuming $m_h = 125 GeV$



- Composite Higgs inspired parametrization (but couplings to fermions and gauge boson allowed to vary independently)
- Fermiophobic Higgs ($c_b = 0$) disfavored
- Apart from SM-like Higgs, another favored region where sign of Higgs couplings flipped

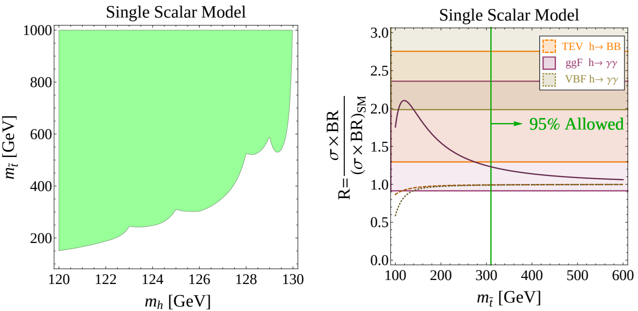
Scalar partner toy model

- Very toy "natural" model: just one scalar top partner (this is not SUSY, where at least two scalar partners are needed)
- Top partner interactions with Higgs to cancel top quadratic divergences

$$-\left(yHQt^c + \mathrm{h.c.}\right) - |\tilde{t}|^2\left(M^2 + 2y^2|H|^2\right).$$

- Only one free parameter: top partner mass $m_{\tilde{t}}^2 = M^2 + y^2v^2$
- New contributions to effective dimension 5 Higgs interactions

$$\frac{c_g}{c_{g,\mathrm{SM}}} = \frac{c_\gamma}{c_{\gamma,\mathrm{SM}}} \simeq 1 + \frac{m_t^2}{2m_{\tilde{t}}^2}$$



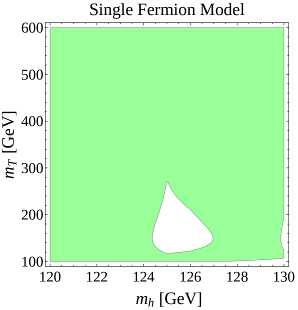
Fermion partner model

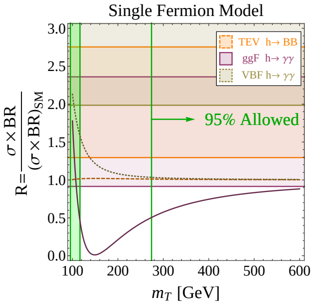
- For fermionic top partner, non-renormalizable interactions with Higgs needed to cancel top quadratic divergence
- Simple model inspired by T-parity conserving Little Higgs

$$-\left(y \sin(|H|/f) Q t^c + \mathrm{h.c.}\right) - y f \cos(|H|/f) T T^c$$

- Again only one free parameter: top partner mass $m_T = y f \cos(v/\sqrt{2} f)$
- New contributions to effective dimension 5 Higgs interactions

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





- Beginning of a beautiful friendship
- More Higgs data from LHC may favor/disfavor particular BSM scenarios...
- ...or just confirm the SM again

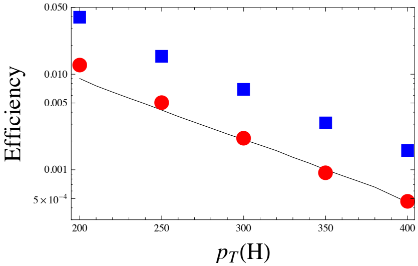
Constraining invisible width

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

- Extending effective theory to add invisible width
- Here χ is a new collider stable particle, possibly constituting part of all of dark matter in the Universe
- Exisiting LHC data already constraint the invisible width Djouadi,AA,Mambrini,Quevillon [1205.3169]

Constraining invisible width

- CMS monojet search EXO-11-059 updated to 5 fb-1
  - at least 1 jet with $p_T^j > 110$ GeV and $|\eta^j| < 2.4$;
  - at most 2 jets with $p_T^j > 30$ GeV;
  - no isolated leptons;
  - missing transverse momentum $p_T^{\mathrm{miss}} \geq 200 - 400$ GeV.
- Event yield dominated by backgrounds (mostly $Z \to \nu\nu$+jets and $W \to \nu l$+jets) with systematics at about 10%.
- For example, for $p_T^{\mathrm{miss}} \geq 350$ GeV CMS observes 1142 events vs predicted background 1224 ± 101
- For Higgs with SM cross section fully invisible additional ~ 100 events, comparable to errors



(red = ggH, blue = VBF)

Constraining invisible width

p_T^{miss}	$N_{\text{inv}}^{\text{ggF}}$	$N_{\text{inv}}^{\text{VBF}}$	ΔN_{Bkg}	$R_{\text{inv}}^{\text{exp}}$	$R_{\text{inv}}^{\text{obs}}$
200	630	260	$\sim$1200	2.6	1.8
250	250	110	$\sim$380	2.0	1.3
300	110	50	$\sim$170	2.1	2.2
350	46	25	101	2.8	1.6
400	22	13	$\sim$70	3.8	2.3

$$R_{\text{inv}}^{\text{ggF}} \equiv \frac{\sigma(gg \to h)}{\sigma_{SM}(gg \to h)} \text{Br}(h \to \text{inv}) \leq 1.9 \qquad @\ 95\%\,CL$$

$$R_{\text{inv}}^{\text{VBF}} \equiv \frac{\sigma(qq \to hqq)}{\sigma_{SM}(qq \to hqq)} \text{Br}(h \to \text{inv}) \leq 4.3 \qquad @\ 95\%\,CL$$

Combining (assuming SM proportions of ggF and VBF),

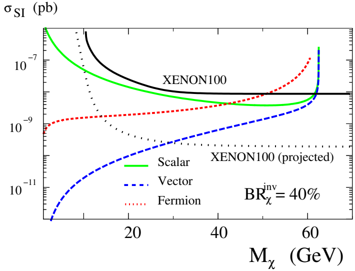
$$R_{\text{inv}} \equiv \frac{\sigma(pp \to h)\text{Br}(h \to \text{inv})}{\sigma(pp \to h)_{SM}} < 1.0(1.3) \qquad @\ 90(95)\%\,CL$$

(*Ignoring theory errors*)

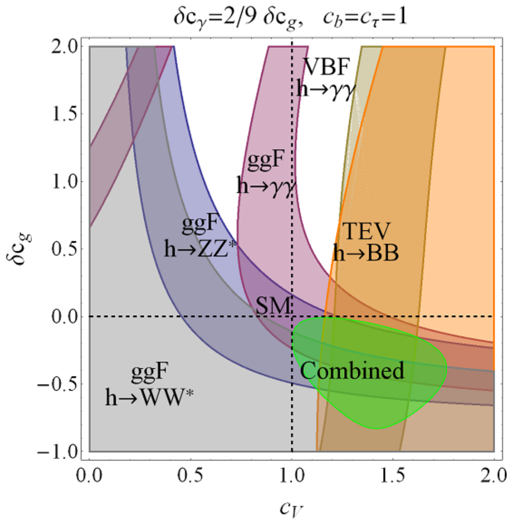
Constraining invisible width

$$R_{\rm inv} \equiv \frac{\sigma(pp \to h){\rm Br}(h \to {\rm inv})}{\sigma(pp \to h)_{SM}} < 1.0(1.3) \qquad @\ 90(95)\%CL$$

- No direct constraints on the invisible franching fraction yet if Higgs produced with the SM rate
- However if Higgs rate enhanced (as for example in the presence of the 4th chiral generation) then our analysis provides non-trivial constraints
- This was just a recast of the large extra dimension search. A designated search could give better bounds?
- Indirectly, a better bound ${\rm Br}(h \to {\rm inv}) < 0.4$ from observation of visible Higgs decays Giardino+ [1203.4254]
- Interesting interplay between LHC and direct dark matter detection in the context of Higgs portal models



What If ?



- Current combined Higgs data allow, while Tevatron and VBF $\gamma\gamma$ channel in CMS favor increased Higgs coupling to WW and ZZ
- What if indeed $c_V > 1$?

What if $c_V > 1$?

- If SM Higgs doublet mixes with a singlet or another doublet, then always $c_V = \cos\alpha < 1$. Thus enhancement impossible in typical SUSY models.
- For Higgs being a pseudo-Goldstone boson of any compact coset (Little Higgs and composite Higgs), also $c_V = \cos(v/f) < 1$. Again, enhancement of c_V impossible
- Low et al [0907.5413] : sum rule proving $c_V > 1$ implies charge-2 Higgs
- AA et al [1202.1532] : stronger sum rule (assuming custodial symmetry)

$$1 - c_V^2 \approx \frac{v^2}{6\pi}\int_0^\infty \frac{ds}{s}\left(2\sigma_{I=0}^{\mathrm{tot}}(s) + 3\sigma_{I=1}^{\mathrm{tot}}(s) - 5\sigma_{I=2}^{\mathrm{tot}}(s)\right).$$

- $c_V > 1$ implies enhancement of isospin 2 channel of WW scattering

Simplest realization of isospin 2 enhancement

- Quintuplet of weakly coupled scalars $Q = \left(Q^{--}, Q^{-}, Q^{0}, Q^{+}, Q^{++}\right)$
- Coupled to electroweak gauge bosons in custodially invariant way

$$\frac{g_Q}{v}\left\{\sqrt{\frac{2}{3}}Q^0\left(m_W^2 W_\mu^+ W_\mu^- - m_Z^2 Z_\mu^2\right) + \left(Q^{++} m_W^2 W_\mu^- W_\mu^- + \sqrt{2} Q^+ m_W m_Z W_\mu^- Z_\mu + \mathrm{hc}\right)\right\}$$

- Sum rule fulfilled for

$$g_Q^2 = \frac{6}{5}\left(c_V^2 - 1\right)$$

Quintuplet and WW scattering

- What is special about $g_Q^2 = 6/5(c_V^2 - 1)$?
- Quintuplet, much like Higgs, contributes to WW scattering but, unlike Higgs, it has *opposite* couplings to W and Z
- For generic $ab \to cd$ process in the limit $g' \to 0$

$$A(s,t,u)\delta^{ab}\delta^{cd} + A(t,s,u)\delta^{ac}\delta^{bd} + A(u,t,s)\delta^{ad}\delta^{bc}$$

  For example $A_{W^+W^- \to ZZ} = A(s,t,u)$,
  $A_{W^+W^+ \to W^+W^+} = A(t,s,u) + A(u,t,s)$, etc

- Isospin singlet and quintuplet contribute as Alboteanu et al [0806.4145]

$$A(s,t,u) = \frac{s}{v^2}\left(1 - c_V^2 \frac{s}{s - m_h^2}\right) + \frac{g_Q^2}{v^2}\left(\frac{s^2}{3(s - m_Q^2)} - \frac{t^2}{2(t - m_Q^2)} - \frac{u^2}{2(u - m_Q^2)}\right)$$

- For $s \gg m_{h,Q}^2$

$$A(s,t,u) \approx \frac{s}{v^2}\left(1 - c_V^2 + \frac{5g_Q^2}{6}\right)$$

  Higgs overshoots unitarization, but for $g_Q^2 = 6/5(c_V^2 - 1)$ quintuplet restores unitary behavior as long as m_Q is not too large

Renormalizable Model

- Quinituplet can be part of renormalizable Higgs sector provided one allows for higher-than-doublet representations under $SU(2)_W$
- Minimal model: scalar Φ in $(3,3)$ representation under *global* $SU(2) \times SU(2)$ (complex triplet + real triplet under $SU(2)_W$)
- Under custodial isospin Φ decomposes as singlet + triplet + quintuplet

$$\begin{pmatrix} \frac{v}{2\sqrt{2}} + \frac{1}{\sqrt{3}}h - \frac{1}{\sqrt{6}}Q^0 + \frac{i}{\sqrt{2}}\pi^0 & -\frac{1}{\sqrt{2}}(Q^+ + i\pi^+) & -Q^{++} \\ -\frac{1}{\sqrt{2}}(Q^- + i\pi^-) & \frac{v}{2\sqrt{2}} + \frac{1}{\sqrt{3}}h + \sqrt{\frac{2}{3}}Q^0 & -\frac{1}{\sqrt{2}}(Q^+ - i\pi^+) \\ -Q^{--} & -\frac{1}{\sqrt{2}}(Q^- - i\pi^-) & \frac{v}{2\sqrt{2}} + \frac{1}{\sqrt{3}}h - \frac{1}{\sqrt{6}}Q^0 - \frac{i}{\sqrt{2}}\pi^0 \end{pmatrix}$$

corresponding to $c_V = \sqrt{8/3}$ and $g_Q = \sqrt{2}$.

- Smaller c_V can be obtained when Φ mixes with EW singlet, or doublet (Georgi,Machacek [(1985)])
- More general Higgs representations under $SU(2) \times SU(2)$ studied in Low,Lykken [1005.0872]

Possible effect on Higgs

- Custodial invariant coupling of Higgs and quintuplet:

$$\mathcal{L}_{hQQ} = -2g_{hQQ}m_Q^2\frac{h}{v}\left(|Q^{++}|^2 + |Q^{+}|^2 + \frac{1}{2}(Q^0)^2\right).$$

  Minimal renormalizable model: $g_{hQQ} = \sqrt{\frac{2}{3}\frac{m_h^2+2m_Q^2}{m_Q^2}}$

- Shifts effective Higgs coupling to $\gamma\gamma$ by

$$\delta c_\gamma \approx \frac{5}{24}g_{hQQ}$$

- Thus, generic prediction of increased Higgs couplings to WW and ZZ, and decreased effective Higgs coupling to photons

Summary

- The puzzle of electroweak symmetry breaking is about to be solved
- Hints from the LHC and other experiments consistently point to weakly coupled electroweak symmetry breaking with a light Higgs boson
- Measuring Higgs coupling may soon give us strong hints favoring or disfavoring particular models beyond the Standard Model
- If data clearly points to $c_V > 1$, all hands on board to search for 5 more Higgs bosons!
- At least *this year* is going to be exciting...