Interpreting Higgs results

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Brussels, 23 Mars 2012

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+ *oven fresh unpublished*

Outline

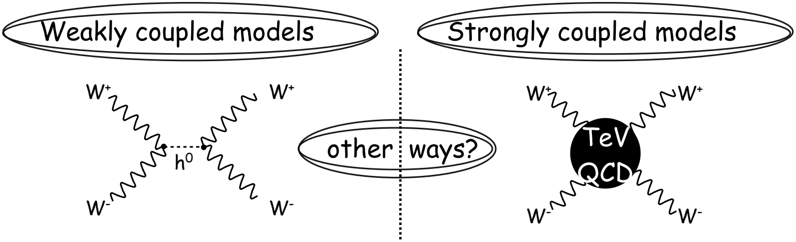
Who broke electroweak symmetry?

- Since LEP we know for a fact fundamental interactions of matter obey $SU(2) \times U(1)$ local symmetry that is however spontaneously broken (non-linearly realized), as W, Z and fermions have masses
- The Question for the LHC is the precise nature of electroweak symmetry breaking
- More rigorously, the question is what sort of physics stops the growth of the scattering amplitudes of W and Z bosons:
  - In the SM (without Higgs) the tree-level amplitude for longitudinally polarized W's and Z's grows with energy, $\mathcal{M} \sim s/v^2$
  - Unitarity requires $\mathrm{Re}\,\mathcal{M}^J < 1/2$ for all partial waves. Perturbative unitarity is lost at TeV
  - Something else must enter before that scale!

Options for Electroweak Symmetry Breaking

3 basic possibilities. Unitarity saved by

- Non-Perturbative effects in the SM (no concrete framework so far)
- Strongly Coupled: composite vectors and/or scalars to WW and WZ
- Weakly Coupled: fundamental scalar coupled to WW and ZZ, otherwise known as the Higgs
- ...or a combination of the above, for example Composite Higgs weakly coupled up to $\sim$ 3 TeV, then strongly coupled



picture stolen from C. Grojean

Only Higgs

- Current experimental data strongly suggest that the weakly coupled option is approximately true, at least for $E \lesssim 1$ TeV, and likely up to much higher scales
    - Electroweak precision tests
    - No new vector or tensor states observed at the Tevatron and LHC
    - Higgs-like excess near 125 GeV
- Furthermore, they point to the simplest realization with a single Higgs boson resposible for unitarizing WW scattering
    - Approximate global symmetries of SM, such as flavor and CP seem to be very well preserved

Why something else than Higgs out there

(almost) Unshakable Arguments

1. Observed `neutrino masses` imply new physics (at least, right-handed neutrinos) somewhere between 1 keV and 10^{15} GeV
2. Existence of `dark matter` requires new physics somewhere between sub-eV and 10^{19} GeV
3. Domination of `matter over anti-matter` requires new physics between 100 GeV and 10^{16} GeV

unfortunately, none of above guarantees new physics showing up in LHC

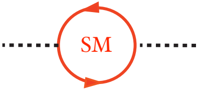
Some Esthetic Arguments

- `Fermion masses and mixings` suggests another sector generating the observed structures, at any scale above TeV and Planck
- Approximate `unification of gauge couplings` suggests new states at any scale between 100 and 10^{14} GeV
- Higgs potential `metastability` suggests new physics between 100 GeV and 10^{10} GeV
- `Instability of Higgs mass` against radiative corrections suggests new states at 100 GeV

only one, somewhat shaky argument clearly points to new physics in LHC

Fine-tuning puzzle

$\delta m_H^2 =$



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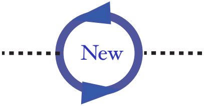

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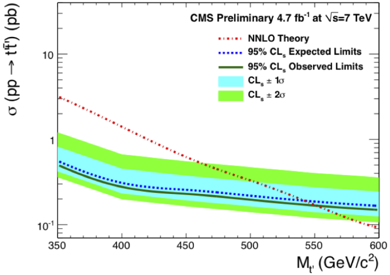
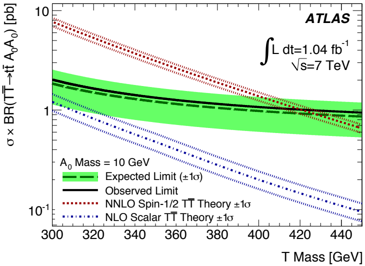
- Hierarchy problem dominated model building for last 30 years
- Two important classes of solutions
  - Supersymmetry: fermion-boson cancellation, may be weakly coupled up to Planck scale
  - Composite/Little Higgs: boson-boson or fermion-fermion cancellation, weakly coupled up to 3-10 TeV, then strongly coupled
- All existing models introduce a multitude of new particles at weak scale, and require serious conspiracy why they preserve approximate accidental symmetries of the SM, to avoid showing up indirectly in numerous precision measurements
- Typically, in specific realizations advertised as natural one has $1 - 0.1\%$ fine-tuning, after experimental constraints are taken into account

Naturalness with fermionic partners

Fermionic top partners T

- Limits depending on dominant decay
- Constraints on $T \to bW$ channel (typically 50% branching ratio in models without T-parity) and on $T \to t$+MET (expected in models with T-parity)
- Current limits on mass around $400 - 500$ GeV
- Naturalness under stress, but not completely dead yet...

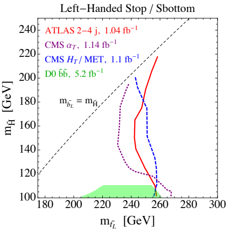


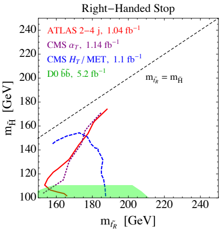


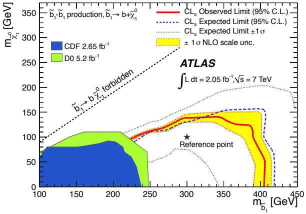
Naturalness with scalar partners

Scalar top partners $\tilde{t}$

- In generic SUSY $m_{\tilde{t}} \gtrsim 1$ TeV $\rightarrow$ serious fine-tuning problem
- But, for $m_{\tilde{t}} \ll m_{\tilde{q}}$ and $m_{\tilde{t}} \ll m_{\tilde{g}}$ limits become much weaker
- Currently only theorist-level robust limit on stops, $m_{\tilde{t}} \gtrsim 150 - 250$ GeV, depending on decay mode and LSP mass Papucci et al [1110.6926]
- Related limits on direct sbottom production from ATLAS [1112.3832]
- Reasonanble fine-tuning still possible if stops and sbottom are only colored superpartner below TeV







Fine

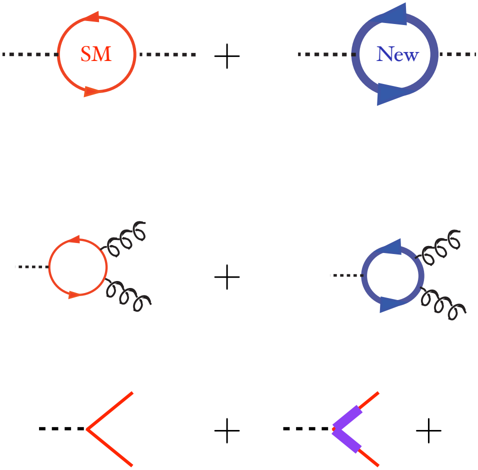
- Naturalness window still half open
- But no experimental hint of a larger framework just around the corner

Dominant attitude in theory:

- Hierarchy problem may or may not be relevant
- Model building now dominated by LHC data, not theory prejudice


IT'S THE
data
STUPID!

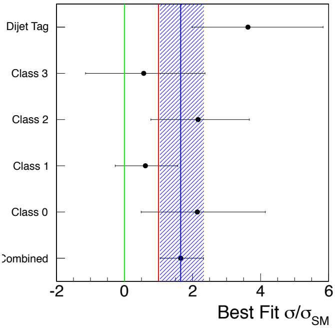

IT'S THE
Higgs
STUPID!

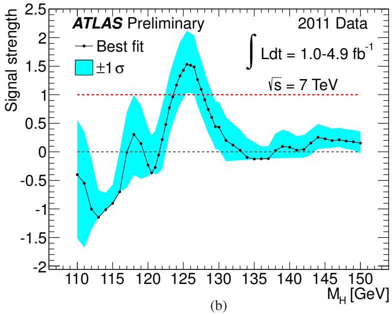


stolen from R. Rattazzi

- The SM Higgs with mass $m_h \sim 125$ GeV has many decay channels that are potentially observable at the LHC and Tevatron
    - Now: $H \to ZZ^*$, $H \to \gamma\gamma$, and $H \to b\bar{b}$
    - Shortly: $H \to WW^*$
    - ~ 1 year perspective: $H \to \tau^+\tau^-$
- Also different production channels can be isolated
    - Now: gluon fusion and (maybe) vector boson fusion
    - Longer Perspective: 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!

Higgs
Observations

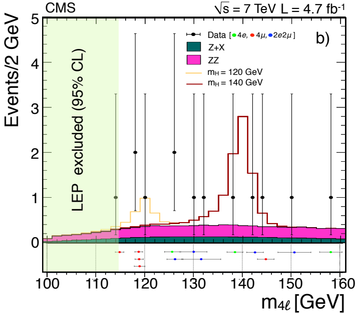


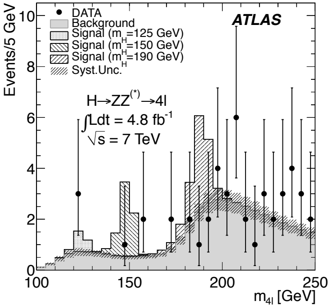


(b)

- 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)

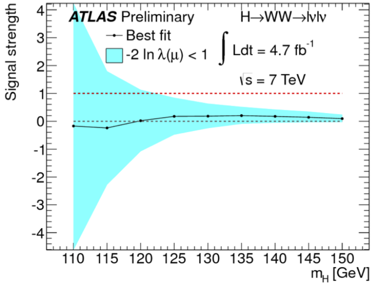
$H \to ZZ^* \to 4l$





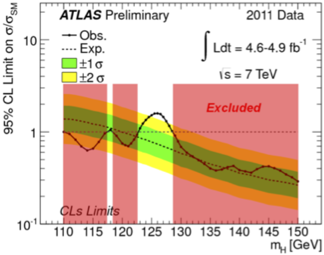
- Very low background, great mass resolution
- ATLAS has 3 events at $m_{4l} \approx 124$ GeV
- CMS has 2 events at $m_{4l} \approx 126$ GeV

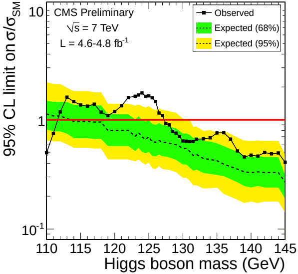
$H \to WW^* \to 2l2\nu$



		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
0-jet	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
1-jet	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
2-jet	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

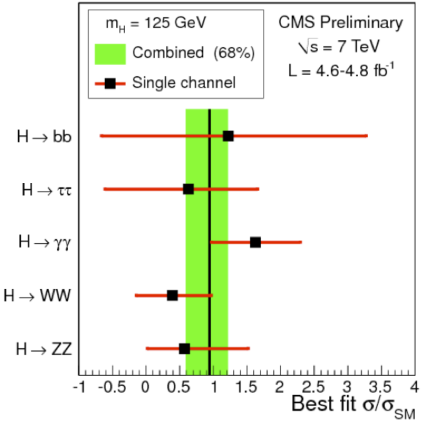
- Significant background, poor mass resolution, better for exclusion than discovery
- No clear excess here, which begins to feel weird
- Bad luck, background misestimation, or something interesting going on?



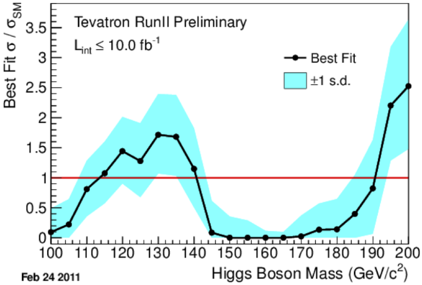


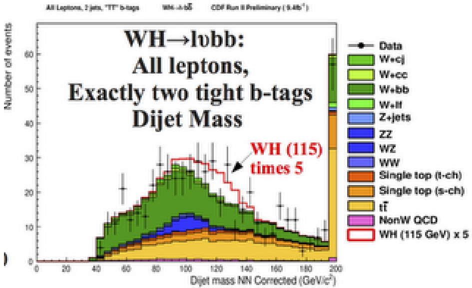
- Low mass range excluded by Tevatron and LHC except for 122-127 GeV range
- Even lower mass range excluded by LEP,
- High mass range excluded by LHC, or highly disfavored by EWPT

Best Fit Cross Section



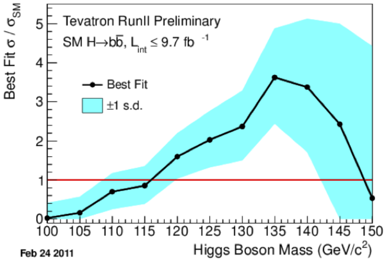
- Slightly too much signal in $\gamma\gamma$ channel
- Slightly too little signal in WW and ZZ channels
- Overall good consistency with SM Higgs predictions

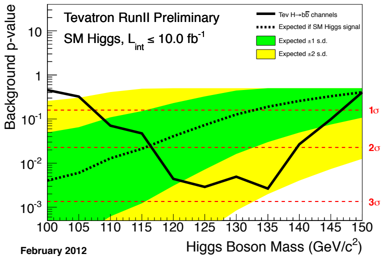




- Broad $\sim$ 3 sigma excess in low mass range, mostly originating from $\sim$ 40 excess events in $W/Z + H \to b\bar{b}$ production mode in CDF
- Consistent with 120-140 GeV Higgs

$VH \to bb$ 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

`Announcement`

The Higgs boson has been discovered at has the mass near 125 GeV

Next Level

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

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

- Only one theoretical prejudice: custodial isospin requires same Higgs coupling to W and Z . Otherwise for $c_W \neq c_Z$:

  $$\Delta T = (c_W^2 - c_Z^2)\alpha_{EM}^{-1} \frac{\Lambda^2}{16\pi^2 v^2}$$

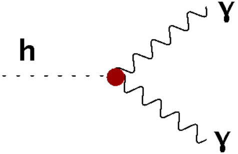
  For $\Lambda \sim 1$ TeV c_W and c_Z have to within 1%
- For time being already assume that $c_\tau = c_b$ (until better $\tau\tau$ data arrive)
- Top already integrated out, contributing to c_g and c_γ
- SM predicts $c_V = c_b = c_g = 1$ and $c_\gamma = 2/9$
- Any of the couplings can be modified in specific scenarios beyond the SM
- All LHC Higgs rates can be easily expressed as functions of the c_i couplings

Higgs Widths

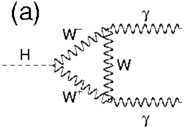
The decay widths of the Higgs relative to the SM predictions are modified approximately as,

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

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



(a)



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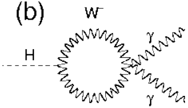


Higgs rates

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

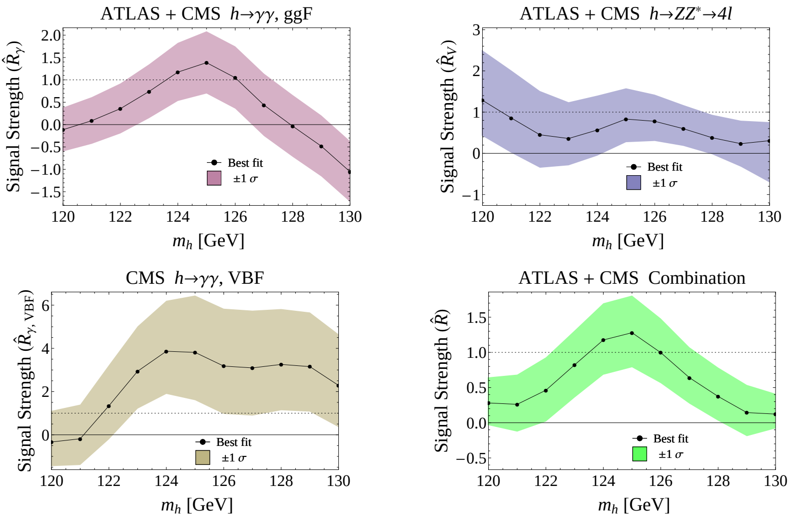
$$\begin{aligned}
R_V &\equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to ZZ^*)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to ZZ^*)} \simeq \left|\frac{c_g c_V}{c_b}\right|^2 , \\
R_\gamma &\equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to \gamma\gamma)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to \gamma\gamma)}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

Effective Theory Interpretation

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

- We will find the region of effective theory parameter space favored by 2011 LHC 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 couplimgs (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] and Espinosa [1202.3697]

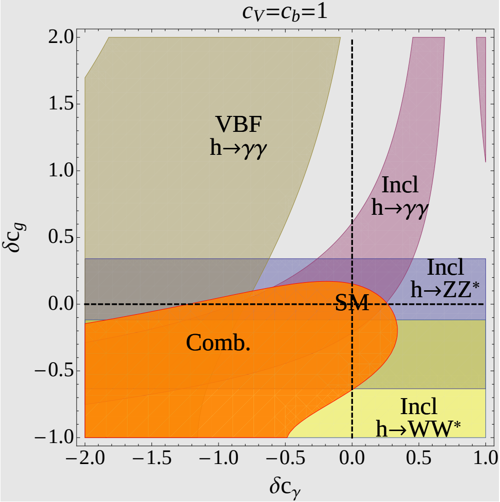
Illegal ATLAS/CMS combination



Carmi et al [1202.3144] , Moriond updates not included, bands are 1 sigma

Fits assuming $m_h = 125$ GeV

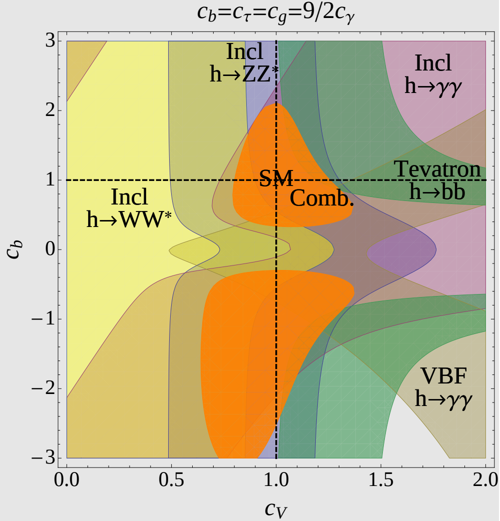
Preliminary



- Only dimension-5 Higgs couplings allowed to vary
- On this plane Tevatron never within 1 sigma band
- Combined $= \chi^2 < 6.25$ (full 4-parameter $\Delta\chi^2$ plots in preparation)

Fits assuming $m_h = 125$ GeV

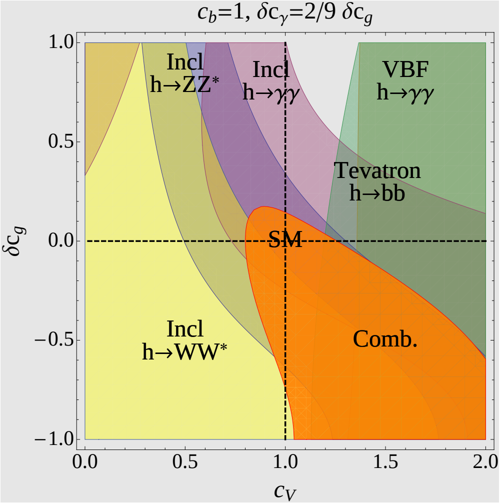
Preliminary



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

Fits assuming $m_h = 125$ GeV

Preliminary



- Higgs coupling to EW gauge bosons, and dimension 5 effective Higgs coupling to gluons allowed to vary
- Top partner models relation $c_\gamma = 2c_g/9$

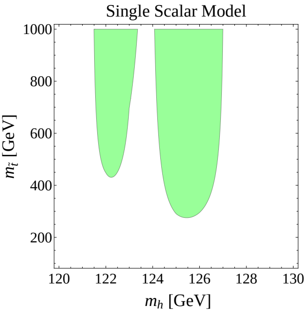
Scalar partner toy model

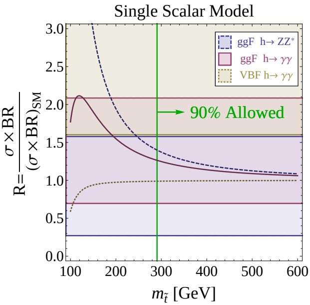
- Very toy "natural" model: just one scalar top partner (this is not SUSY, where at least two scalar partners are needed)
- Top partner interactions with Higgs to cancel top quadratic divergences

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

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

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





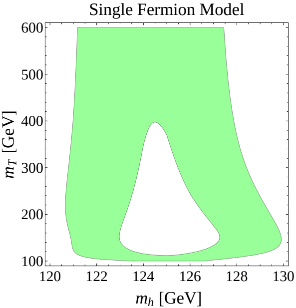
Fermion partner model

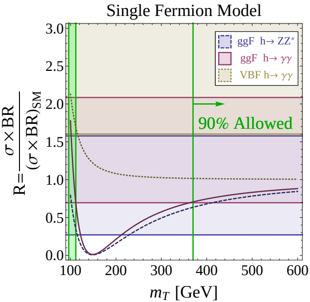
- For fermionic top partner, non-renormalizable interactions with Higgs needed to cancel top quadratic divergence
- Simple model inspired by T-parity conserving Little Higgs

$$-\left(y\sin(|H|/f)Qt^c + \mathrm{h.c.}\right) - yf\cos(|H|/f)TT^c$$

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

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

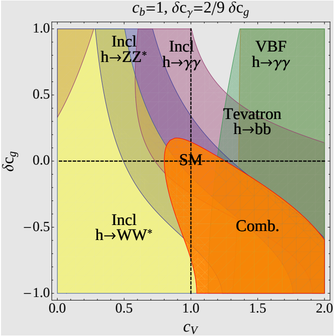




- Beginning of a beautiful friendship
- More Higgs data from LHC may favor/disfavor particular BSM scenarios...
- ...or just confirm the SM again

What If ?

One more thing...



- 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)

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

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

Quintuplet Higgs?

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...