Beyond the Standard Model Higgs Theories for Beyond the Standard Model Higgs Couplings

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2012 LHC analyses have confirmed excesses of 2011
Higgsteria

Science Advocates

Why is it important that we have found the Higgs?

Oh! It has future applications in propulsion, energy creation, data transmission, you name it!

Scientists

Why is it important that we have found the Higgs?

Because it's fucking awesome.
We’ve discovered something that looks like the Higgs, but is it a standard Higgs?

Post-discovery, emphasis is on coupling measurements

Question: What are theory implications of coupling measurements?
Two directions:

I) Couplings to down-type fermions suppressed?
In 1206.1058 (w/ Azatov, Craig, Galloway), we find this disfavors minimal SUSY

II) Coupling to gauge bosons enhanced?
In 1207.0493 (w/ Newby, Raj, Wanotayaroj), we explore extended Higgs sectors that allow this
Coupling notations

Theorist conventions for gauge coupling

\[ a \equiv \frac{g_{hWW}}{g_{hWW}^{SM}} \]

Fermion couplings

\[ c_X \equiv \frac{g_{h\bar{X}X}}{g_{h\bar{X}X}^{SM}} \]

Normalized to 1 for SM value
Fits to recent data

Comparison of experiment and theory

CMS 2012 Fit

1207.1693 Ellis, You
Fermion couplings indirectly constrained now

Top: through rate for gluon fusion (tth is starting to be analyzed)

Bottom/tau: through effects on other branching ratios (h → bb, ττ search becoming more important)
Our fit to CMS 2011

VBF $\gamma\gamma$ preferred large $a$

WW, ZZ channels preferred smaller $a$, $c_b$ and larger $c_t$

Sensitive to what data is used: e.g. Tevatron, LHC 2012
Lack of down-type events

So far, down-type decays have no large excesses

Suggestive, but need more data
SUSY implications
Type II Two Higgs Doublet Model

General mixing angles allow suppressed down-type couplings

$$a \equiv \frac{g_{hVV}}{g_{hVV}^{SM}} = \sin(\beta - \alpha),$$

$$c_t \equiv \frac{g_{htt}}{g_{htt}^{SM}} = \frac{\cos \alpha}{\sin \beta},$$

$$c_b \equiv \frac{g_{hb\bar{b}}}{g_{hb\bar{b}}^{SM}} = -\frac{\sin \alpha}{\cos \beta},$$

Yukawa Couplings: General Type–II 2HDM

"Up–Suppressed"

"Down–Suppressed"
Our Approach

- Analyze general two Higgs doublet model
- Determine a condition to get down-type couplings suppressed, assuming $\tan \beta > 1$
- Apply to SUSY scenarios
- Upshot: coupling measurements constrain SUSY models much like Higgs mass
Potential

Most general quartics for neutral Higgses in 2HDM (sorry for nonstandard notation)

\[ V = \lambda_1 |H_u^0|^4 + \lambda_2 |H_d^0|^4 - 2\lambda_3 |H_u^0|^2 |H_d^0|^2 + \left[ \lambda_4 |H_u^0|^2 H_u^0 H_d^0 + \lambda_5 |H_d^0|^2 H_u^0 H_d^0 + \text{c.c.} \right] \]

Condition for down-type suppression

\[ |\sin \alpha| < |\cos \beta| \]

We find a single required condition on quartics
Condition

\[ \lambda_1 \sin^2 \beta - \lambda_2 \cos^2 \beta - \cos(2\beta)\lambda_3 + \frac{\sin 3\beta}{2 \cos \beta} \lambda_4 + \frac{\cos 3\beta}{2 \sin \beta} \lambda_5 < 0 \]

For MSSM, \( \lambda_1 = \lambda_2 = \lambda_3 > 0 \), so cannot be satisfied for \( \tan \beta > 1 \)

Radiative corrections only help in \( \alpha_{\text{eff}} \) scenario (Carena et.al.)
For nonminimal SUSY

NMSSM with large $\lambda$ $S H_u H_d$ helps condition
(see for e.g. Hall et.al.)

Nondecoupling D-terms that maintain
D-flat direction do not work

We’re currently looking into SUSY + Technicolor

Conclusion: Future analyses of $b\bar{b}$, $\tau\bar{\tau}$ can rule out minimal SUSY
Enhanced couplings to $WW/ZZ$ (1207.0493)

- Higgs coupling fits are model-independent, allowing all values of $a, c$
- Enhanced gauge couplings are constrained theoretically (requires doubly-charged Higgs)
- Looked at consistent theories (Georgi-Machacek) and their phenomenology
Requirement of doubly-charged Higgs shown by Low, Rattazzi, Vichi and Falkowski, Rychkov, Urbano

Can be shown by unitarity

\[ W_L^+ W_L^+ \rightarrow W_L^+ W_L^+ \]

Unitarized if

\[ \sum_i a_{h_i}^2 \frac{W W}{W W} = 1 \]
Doubly-charged Higgs allows enhanced a s-channel constructively interferes with SM amplitude

\[-a_h^2 W^- W^+ + \sum_i a_{h_i}^2 W W = 1\]
Georgi-Machacek Model

Model with large breaking allowed by triplets

\[
\phi = \begin{pmatrix} \phi^0* & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}
\]

Transform as \((2, \bar{2}), (3, \bar{3}) : SU(2)_L \times SU(2)_R\)

Diagonal vevs break to custodial SU(2), allow large triplet vev contribution

\[
<\phi^0> = \frac{v \cos \theta_H}{\sqrt{2}}
\]
Under custodial SU(2), Higgs states consist of

Neutral singlets

Triplets

Quintuplet

Doubly charged Higgs in $H_5$

$$H_1, H'_1$$

$$\left( H^-_3, H^0_3, H^+_3 \right)$$

$$\left( H^{--}_5, H^-_5, H^0_5, H^+_5, H^{++}_5 \right)$$

$$a_{H_1} = \cos \theta_H, \ a_{H'_1} = \sqrt{8/3} \sin \theta_H$$
Singlets mix leading to two mass eigenstates

\( h_1 \) is taken to be Higgs that has been discovered with couplings \( a_1, c_1 \)

This fixes \( h_2 \) couplings

Constraints on \( Z \to bb \) shown in tan and gray (Haber, Logan)
Near negative c point: couplings are strong enough to push $h_2$ above SM Higgs searches of 600 GeV

Near SM point: suppressed couplings, can be searched for in regions where SM Higgs is ruled out

In parts of parameter space, $h_2$ cascade decays to tops or $h_1$ pairs can also be important!

$$R = \frac{\sigma(pp \to h_2)}{\sigma(pp \to h_{SM})} \times \frac{Br(h_2 \to WW)}{Br(h_{SM} \to WW)}$$
The lefthand plot in Fig. 7 is an example of the modifications to the GM model, where higher charges are both positive, demonstrating the destructive interference to the loop effects. As shown in the generalizations to the GM model, the charged scalars can induce corrections to the Higgs quartics affecting cleanly, we consider the loop diagrams of the charged scalars. When the couplings in Eq. (2) tend to destructively interfere, leading to a smaller decay rate into photons. In particular, the contributions with the same sign as the top quark, hence, in the GM model, the charged scalars in induce corrections to the Higgs decays to photons, taking into account only the effects accounted for. Just out last night, 1207.1718 also looked at GM model and fits.
Model dependent pheno

$H^{++}$ can be searched for in single production through WW fusion and its decays back to same-sign leptons (see Chiang et.al. 1202.2014)

With complicated Higgs sector, it is possible to have $W/Z$ cascades as well as decays into pairs of lighter Higgs particles
Looking to the Future
Is it a standard or nonstandard Higgs? Couplings can tell us a lot!
Conclusions

- Post-discovery, need to understand Higgs
- Early days, but worth anticipating implications of certain Higgs couplings
- Current data suggests nonstandard behavior with strong theoretical implications
- Expect ~ 15-20 fb$^{-1}$ more data, which will be very interesting!
Thanks!