Higgs Physics with a Universal Higgs-Fermion Coupling

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20 December 2002

Abstract
A variant of the conventional Higgs model is proposed which separates the physics of the Higgs decay modes from the problem of fermion mass generation. The lowest mass Higgs boson has no significant $b\bar{b}$ decay mode but a $c\bar{c}$ and $u\bar{u}$ branching ratio of about 33% each and requires the existence of two Higgs doublets of type II, which is consistent with supersymmetric models. It also implies there are probably no photon or gluon decay modes of any Higgs boson.

1 General Introduction
The Standard Model incorporates mass in two different but related ways. Firstly the $W$ and $Z$ bosons obtain masses by the spontaneous breaking of the $SU(2) \times U(1)$ electroweak symmetry. Three of the four components of the complex scalar doublet Higgs field become associated with the weak bosons while the fourth remains as a scalar particle, the Higgs boson. The values of the masses are fixed by electroweak couplings. Secondly the fundamental fermions, quarks and leptons, obtain their masses by Yukawa couplings to the Higgs field. Each fermion has its own unique Yukawa coupling constant, which is not related to the electroweak couplings in any known way. This means that the values of the fermion masses are unknown and not computable in the Standard Model. Although this is an unsatisfactory situation, it is accepted in the absence of any better idea.

The Minimal Supersymmetric Standard Model (MSSM) has basically the same two mechanisms. However it incorporates two complex Higgs doublets—one gives masses to the weak isospin $+1/2$ fermions ($u$, $c$, $t$ quarks and possibly the neutrinos) while the other gives masses to the weak isospin $-1/2$ fermions ($d$, $s$, $b$ quarks and the charged leptons). In the MSSM there are five unused components of the Higgs fields, after giving masses to the $W$ and $Z$ bosons, which leaves three neutral Higgs particles and a pair of charged Higgs particles.

The SM and MSSM do not explain the family (generation) structure of the fermion masses. Each fermion has an arbitrary Yukawa coupling, apparently independent of the family it belongs to and whether it is a quark or lepton. New physics is required to explain the family structure and the quark CKM matrix, even in the Standard Model.

This note proposes a modification to the fermion mass generation mechanism which also requires new physics but without specifying what that physics is. Nevertheless it makes concrete predictions for the decay modes of the Higgs particles, some of which can be tested with the current data. The basic philosophy is to separate an intractable problem into an easy part plus an unknown part in the hope that an experimental verification of the easy part will lead others to solve the unknown part.

2 The Introduction to this Proposal
We start with the observation that a Higgs-fermion Yukawa coupling (spin 0 to spin 1/2) is a reasonable thing to have but the existence of 9 (or 12) different couplings, simply to fit 9 (or 12) different fermion masses, is not. It would be far simpler and more in the spirit of the rest of particle physics to have just one, universal, Yukawa coupling. At a stroke this would nearly halve the number of undetermined constants in the Standard Model. Of course, this would result in all fermions having the same mass.

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if the Higgs mechanism were the only contribution to the fermion mass. By assuming that there are one or more additional contributions to the fermion mass generation, we can separate the physics of the branching ratios of the Higgs decay modes from the understanding of the fermion mass values. Multiple contributions to the observed mass is already an accepted concept for the proton and neutron and also for electrons in condensed matter.

A second observation is that the LEP I and SLC data [9] suggest that a Higgs boson exists with a mass of about 80–90 GeV/c^2, albeit with large uncertainties. This is partially in conflict with a direct search for the Higgs particle, where a limit of about 114 GeV/c^2 has been obtained [10] at LEP II. However on closer examination, it should be noted that the indirect search result only really depends on the Z-Higgs couplings of the theory while the direct search result assumes that the Higgs boson decays predominantly to b quarks.

The proposal in this note does not alter the Z-Higgs coupling so the indirect search result is taken as valid. However the direct search result is no longer valid if there is a universal Higgs-fermion coupling constant.

3 A Universal Higgs-Fermion Coupling in the Standard Model

With a universal Higgs-fermion coupling, the following decay modes exist for a low mass Higgs:

\[ H^0 \rightarrow e^+e^- \mu^+\mu^- \tau^+\tau^- \nu_e\bar{\nu}_e \nu_\mu\bar{\nu}_\mu \nu_\tau\bar{\nu}_\tau \ u\bar{u} \ d\bar{d} \ s\bar{s} \ c\bar{c} \ b\bar{b} \ t\bar{t}. \]

In order to compute the branching ratios, we need to give each quark decay mode a weight of three to account for the three colours of quarks and anti-quarks. In addition each decay mode should also be doubled for left- and right-handed spin states. This then raises the question of whether this doubling is valid also for the neutrinos.

A few years ago it would have been reasonable to assume that no neutrino decay modes should exist at all. However the existence of neutrino oscillations [11] and the proposed see-saw mechanism [12, 13] of neutrino masses has led to the suggestion that left-handed neutrinos (and right-handed anti-neutrinos) might have masses similar to their charged partners and that right-handed neutrinos (and left-handed anti-neutrinos) might have enormous masses. So it seems reasonable, now, in a model with a universal Higgs-fermion coupling to include neutrino decay modes. The question is whether to incorporate one spin state or two. This is left for experiments to decide.

For an 80 GeV/c^2 Higgs boson the top quark decay mode is not possible. This leaves 39 or 42 (approximately) equal decay modes (counting spins and colour states) with each one then having a branching ratio of 2.6% or 2.4%. For example:

- \( \text{BR}(H^0 \rightarrow \text{any charged lepton pair}) = 5\% \)
- \( \text{BR}(H^0 \rightarrow \text{any } q\bar{q}) = 14.5\% \)
- \( \text{BR}(H^0 \rightarrow \text{all } q\bar{q}) = 72\% \)
- \( \text{BR}(H^0 \rightarrow \text{all } \nu\bar{\nu}) = 7.2\% \text{ or } 14.4\% \)

The fatal flaw with this scheme is the 5% decay mode to \( e^+e^- \). This would imply that electron positron collisions would produce a Higgs boson resonance around a centre-of-mass energy of 80 GeV/c^2, which LEP and SLC experiments have definitely not seen.

However there are a few ways to reconcile a universal Higgs-fermion coupling with the Standard Model. One is to assume that the Higgs mass is greater than 200 GeV/c^2 in order to avoid conflicts with unseen \( e^+e^- \) resonances but this is clearly incompatible with the low mass suggested by the indirect Higgs search data. Another possibility arises when it is remembered that the Higgs boson has W and Z decay modes as well as fermion/anti-fermion decay modes. In order to compute the correct branching ratios, it is necessary to know the ‘baseline mass’ that the universal Higgs-fermion coupling constant provides. (This is the degenerate mass all fermions have before additional interactions break the degeneracy.)

If the ‘baseline mass’ is very large (\( > M_Z \)), then the fermionic decay modes will dominate over the weak boson decay modes, whatever the Higgs mass. For a ‘baseline mass’ about equal to \( M_Z \), the weak boson decay modes will take an equal share (per spin state) with each fermion decay mode for a Higgs mass of more than 100 GeV/c^2, since off-mass-shell weak boson pair decays start to become
significant. Still this does not seriously reduce the $e^+e^-$ decay mode. Only if the ‘baseline mass’ is a lot less than $M_Z$ would the weak boson decay modes dominate and squeeze out the fermionic decay modes.

Although the ‘very small baseline mass’ scenario cannot be ruled out a priori, it does seem rather contrived and unconvincing when we might expect that the ‘baseline mass’ should either be close to the weak boson masses, the top quark mass or perhaps the Higgs energy scale of about 250 GeV. Things are quite different for physics beyond today’s Standard Model.

4 The Universal Higgs-Fermion Coupling Concept in Two Higgs Doublet Models (2HDM)

In models with two Higgs doublets (2HDM) there are three neutral Higgs bosons and two charged Higgs bosons. These are usually labeled $h^0$, $H^0$, $A^0$, $H^-$ and $H^+$. However we will label the first two neutral Higgs particles as $H_u^0$ and $H_d^0$ to signify the former couples to the upper-level (weak isospin +1/2) fermions while the latter couples to the lower-level (weak isospin −1/2) fermions. This is the case for type II 2HDM, of which the MSSM is an example.

To begin with we will ignore any mixing between these two neutral Higgs bosons, that is, the mixing angle $\alpha = 0$. The fermionic decay modes are:

$$
\begin{align*}
H_u^0 &\rightarrow \nu_\mu \nu_\mu, \quad \nu_\mu \nu_\mu, \quad \nu_\tau \nu_\tau, \quad u\bar{u}, \quad c\bar{c}, \quad t\bar{t} \\
H_d^0 &\rightarrow e^+e^-, \quad \mu^+\mu^-, \quad \tau^+\tau^-, \quad d\bar{d}, \quad s\bar{s}, \quad b\bar{b}
\end{align*}
$$

As with the Standard Model, each listed quark decay mode comes in three colour states and two spin states; each lepton decay mode comes in two spin states (or maybe only one each for the neutrinos).

In order to be compatible with the indirect search result of a round 80 GeV/c$^2$, the lowest mass Higgs boson must then be $H_u^0$ to avoid having $e^+e^-$ decay modes. This is the boson that is usually labeled as $h^0$ and which implies that $\tan \beta$ (the usual ratio of the Higgs vacuum expectation values) is less than one. There are a number of experimental consequences.

Firstly, for a universal coupling constant, we would expect an 80 GeV/c$^2$ $H_u^0 (h^0)$ to have 15 or 18 decay modes, counting spin and colour states separately. Thus

$$
\text{BR}(H_u^0 \rightarrow u\bar{u}) = \text{BR}(H_u^0 \rightarrow c\bar{c}) = 40\% \text{ or } 33\%
$$

There would thus be a branching ratio of 80\% (or maybe 66\%) to hadrons and a branching ratio of 20\% (or 33\%) to invisible states. Since $u\bar{u}$ decay modes would be difficult to tag at LEP, only the charm decay modes would be identifiable and not very easily. They could well have gone unnoticed, especially for a Higgs mass close to that of the $Z$ where the dominant background is $ZZ$.

The second experimental signature would be the clear resonance in $e^+e^-$ collisions at the mass of the $H_d^0 (H^0)$, which has to be greater than 200 GeV/c$^2$, otherwise it would have been seen at LEP II. The $H_d^0$ has 24 decay modes counting spin and colour states separately. This implies:

$$
\begin{align*}
\text{BR}(H_d^0 \rightarrow d\bar{d}) &= \text{BR}(H_d^0 \rightarrow s\bar{s}) = \text{BR}(H_d^0 \rightarrow b\bar{b}) = 25\% \\
\text{BR}(H_d^0 \rightarrow e^+e^-) &= \text{BR}(H_d^0 \rightarrow \mu^+\mu^-) = \text{BR}(H_d^0 \rightarrow \tau^+\tau^-) = 8.3\%.
\end{align*}
$$

The $H_d^0$ would also appear as a resonance if a muon collider were ever built and in proton-proton and proton-antiproton collisions because of the $Hd\bar{d}$ coupling. For hadron colliders the charged lepton decay modes of $H_d^0$ would be obvious signatures.

These straightforward predictions are again subject to modifications depending on the ‘baseline mass’ of the Higgs mechanism but only if the Higgs mass is more than about 100 GeV/c$^2$. For a ‘baseline mass’ of about the $Z$ mass, the above fermionic decay modes would be reduced as there would be $W/Z$ decay modes of equal strength. If the ‘baseline mass’ were significantly less than the $Z$ mass then the fermionic decay modes would be replaced by $W$ and $Z$ decay modes.

If there is mixing between $H_u^0$ and $H_d^0$ then the unwanted $e^+e^-$ decay modes of the lightest neutral Higgs boson could again wreck this model. Although this could be suppressed by choosing different universal Yukawa couplings for each Higgs doublet—and thus different ‘baseline masses’—it would seem that demanding very small or zero Higgs doublet mixing is the only realistic way of reconciling the universal Higgs fermion coupling idea with an 80 GeV/c$^2$ $H_u^0$. 

The $A^0$ Higgs boson has no weak boson decay modes in a 2HDM of type II. They decay to upper-level (weak isospin $+1/2$) fermions proportional to $1/\tan \beta$ and to lower-level (weak isospin $-1/2$) fermions proportional to $\tan \beta$. Since $\tan \beta$ is less than one here, this would imply that the $A^0$ has decay modes similar (but not identical) to the $H^0_u$ although it might be able to decay to top quarks if its mass is great enough. Of course, the top decay mode would not dominate as it does in conventional Higgs models.

The charged Higgs bosons would also have universal couplings to the fermions giving rise to decay modes very much like $W$ bosons.

5 Theoretical Implications

The existence of a Higgs boson with a universal Higgs-fermion coupling would seem to imply the need for a two Higgs doublet model (2HDM) of type II. This could be realised within a supersymmetric theory and its discovery could provide the first evidence for SUSY before any SUSY partner particles are observed.

The explanation for the different fermion masses—the breaking of the mass degeneracy provided by this variant of the Higgs mechanism—clearly requires new physics. (Of course, unless the Yukawa coupling constants are taken as inexplicable fundamental constants, a similar statement is also true in the conventional SM and MSSM.) This paper does not attempt to propose what the new physics would be. However it is possible to outline some of the ingredients and consequences of the new physics. The following discussion assumes a SUSY theory.

Firstly, it seems reasonable to assume that both fermions and their SUSY partners have the same universal Higgs coupling and thus all have the same ‘baseline mass’, perhaps around several hundred GeV/c². Some new interaction would then act upon the R-parity quantum number and lower the ‘normal’ fermions to a smaller mass and lift the SUSY partner particles to a larger mass. A second stage would presumably cause further shifts (‘splitting’) according to the family (generation) quantum number, of which little is currently known. The final particle masses would presumably appear after additional shifts caused by colour and electroweak interaction effects.

It would be natural that quarks with their colour interactions would have bigger masses than leptons in a given family/generation. Furthermore, charged leptons would be expected to be heavier than neutral leptons because of electric interactions and similarly charged 2/3 quarks would be expected to be heavier than charge 1/3 quarks. That this is not true for $u\bar{u}$ and $d\bar{d}$ could be due to $Z$ boson effects overwhelming photon effects, since the so-called 1st generation quarks are shifted by a very large energy amount from the ‘baseline mass’ value.

If the fermions and their SUSY partners do share the same universal coupling then, for Higgs interactions, SUSY is effectively an unbroken symmetry. This implies that any Feynman diagram with a Higgs boson coupling to a fermion loop will have a cancelling diagram with a SUSY partner loop. This cancellation will be exact. The consequence of this is the elimination of all higher order loop corrections to the allowed decay modes and also the removal of all Higgs decay modes to photons and gluons. (This latter effect has profound implications for experimental physics searches for the Higgs.)

Having no Higgs decay modes to photons and gluons removes any possibility for truly massless particles to interact with the Higgs field in the vacuum. This is clearly self-consistent. (Could it be that the Standard Model, and conventional broken SUSY, without this exact cancellation of loops, is not self-consistent?)

6 Alternative Variations

This proposal has dealt with a single, universal, Yukawa coupling constant scenario. The conventional view is that there are 9 or 12 such constants. Clearly there is room for any number of Yukawa constants from zero up to 9 or 12.

Zero constants might seem an attractive idea with the Higgs mechanism having no direct part in generating fermion masses. In the Standard Model there might still be an indirect effect via weak boson loops although there might be cancellations in a SUSY model. However the main reason for not including these ideas is that they are unnecessary. It is simpler to assume that the fermions have the same coupling to the Higgs field as the SUSY fermions. This also makes the model easier to test experimentally.
developing this idea in this paper is the reasonableness of having a Yukawa coupling. Some explanation for removing it would need to be found.

Two Yukawa couplings is still a possibility in a 2HDM—one constant for each Higgs doublet. Three Yukawa couplings might make sense with one for each family/generation. However it would probably imply a large $b$ quark decay mode, incompatible with an $80\,\text{GeV}/c^2$ Higgs boson. Four Yukawa constants could give masses for each fermion in a family with other interactions splitting each family. However this idea probably founders because there is no clear repeated pattern of masses seen within the three families.

7 Conclusions

The Standard Model and conventional SUSY variants of the Standard Model incorporate multiple Yukawa couplings between Higgs bosons and fermions in order to account for the different fermion masses. This paper proposes that there is only a single, universal Higgs-fermion coupling constant. In order to be compatible with experimental data, this concept appears to require at least a two Higgs doublet model of type II, such as a supersymmetric theory.

If so, the lightest Higgs boson, $h^0$, could be (but does not have to be) lighter than the currently accepted limits, possibly as low as $80\,\text{GeV}/c^2$. Its visible decay modes would be to up and charm, each of about 33%, or possibly 40% if there are no couplings to right-handed neutrinos. The heavier neutral Higgs boson, $H^0$, should be easy to detect in electron positron, muon and hadron colliders and its mass is greater than $200\,\text{GeV}/c^2$. The charged lepton pair decay modes with branching ratios of 8.3% should be straightforward, whatever the collider. The $b\bar{b}$ decay mode at 25% could be exploited using charm tagging techniques. There would probably be no decay modes to photons or gluons.

In a sense, this paper has advocated less physics, namely only a single Yukawa coupling constant. However it does imply the existence of new physics to explain the breaking of the fermion mass degeneracy. Since even the Standard Model requires new physics to explain the values of the multiple Yukawa constants, that fact ought not to count against this proposal.

Acknowledgements

I would like to thank the following for assistance and encouragement: Kate Fenton, Tony Guénault, Rich Haley, Stephen Haywood, Holly Thomas and Anne Watson.

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