New Charged Particles from Higgs Couplings

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Abstract

The recently reported observation of a new particle with mass about 125 GeV and couplings generally resembling those of the Standard Model Higgs boson provides a potential probe of the physics of electroweak symmetry breaking. Although the current data only provides hints, we suggest a particular combination of Higgs couplings as an assay for new charged particles connected with electroweak symmetry breaking, and construct a simple model with charge 5/3 quarks as a demonstration of its use.
I. INTRODUCTION AND CONCLUSIONS

The CMS and ATLAS collaborations have recently reported[1] the near-discovery of a new particle whose properties are generally consistent with those of the Standard Model (SM) Higgs boson. Such a discovery would herald the start of a new era in our quest to understand the physics of electroweak (EW) symmetry breaking. While experimenters continue to refine their measurements of the mass and couplings of this new state, theorists have already begun the daunting task of interpreting these results in the context of existing ideas for the origin of electroweak symmetry breaking and beyond the SM physics[2–15].

What observations indicate that a new particle $h$ is directly connected with the physics of electroweak symmetry breaking? Broadly speaking the particle should have interactions reflective of the electroweak symmetry breaking masses of the SM fermions and gauge bosons. But somewhat paradoxically some of the best information on the nature of electroweak symmetry breaking is likely to come from the couplings to the gauge bosons that do not acquire electroweak breaking masses, the gluons and the photon. The couplings of a Higgs-like state to gluons and photons probe the quantum corrections coming from the SM fermions and gauge bosons as well as those from any new states that carry charge or color and couple, directly or indirectly, to the physics of electroweak symmetry breaking. Therefore the quantum-induced couplings $hGG$ and $hFF$ are a useful discriminant for models of EW symmetry breaking, can help test naturalness of this symmetry breaking, and may be one of the earliest indicators of the existence of charged particles beyond those of the SM.

Consider the addition to the standard model of a new fermion $\psi$ in a color representation $R$ carrying electric charge $Q$. If this new fermion couples to the physics of electroweak symmetry breaking we expect its mass to vary with the electroweak-breaking vev $v \sim 246$ GeV. But generally not all of the fermion’s mass will arise from electroweak breaking and the mass parameter is a function of $v$: $m_\psi(v)$. Then the (non-derivative) coupling to the Higgs $h$ is $dm_\psi/dv$. Our convention is $m_\psi \geq 0$ so a positive value for $dm_\psi/dv$ increases the fermion mass in the presence of electroweak breaking while a negative value decreases it.

The contributions of the new fermion $\psi$ to the $hGG$ and $hFF$ couplings at one loop are easily calculated[16]. We can parameterize the new contributions to $h$ couplings to gluons

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1 We simplify the discussion by restricting to a SM Higgs doublet. Our discussion is easily generalized to more complex Higgs sectors.
and photons as in [2]:

$$\delta L = \delta c_g \frac{\alpha_s}{12 \pi v} hG^2 + \delta c_\gamma \frac{\alpha}{\pi v} hF^2$$

(1)

With this parameterization the top quark loop contributes (in the limit $2m_t \gg m_h$) $\delta c_g = 1$ and $\delta c_\gamma = (2/3)^2/2 = 2/9$. For a general fermion the results are

$$\delta c_g = 2 I(R) \frac{d m_\psi}{d v} \frac{v}{m_\psi} A_f(x_\psi) = 2 I(R) \frac{d \ln m_\psi}{d \ln v} A_f(x_\psi)$$

$$\delta c_\gamma = \frac{Q^2}{6} D(R) \frac{d m_\psi}{d v} \frac{v}{m_\psi} A_f(x_\psi) = \frac{Q^2}{6} D(R) \frac{d \ln m_\psi}{d \ln v} A_f(x_\psi)$$

(2)

where $I(R)$ and $D(R)$ are the index and the dimension of the color representation $R$ respectively, $x_\psi \equiv (m_\psi/2m_\psi)^2$ and $A_f(x) = 3 [(x - 1)f(x) + x] / (2x^2)$ where $f(x) = \arcsin^2 \sqrt{x}$ for $x \leq 1$. Note that $A_f(x)$ is very close to unity for fermion masses larger than the $h$ mass.

The relations eq. (2) already provide a useful result: the ratio of the deviation in the couplings of the $h$ to photons and gluons is independent of the mass and (non-zero) coupling of the new fermion and is a measure of the fermion charge:

$$\frac{\delta c_\gamma}{\delta c_g} = 2 \frac{Q^2}{12} \frac{D(R)}{I(R)} = \frac{2}{3} \frac{Q^2}{C_2(R)}$$

(3)

The last equality follows from the relation between the index of a representation and its quadratic Casimir, $C_2(R) D(R) = I(R) D(G)$ with $D(G) = 8$ for $SU(3)$. A measurement of $\delta c_\gamma/\delta c_g$ is a measurement of $Q^2/C_2(R)$ for the heavy fermion, solely from Higgs physics.

Several comments are in order:

1. Increasing the mass of the heavy fermion relative to its EW symmetry breaking mass contribution decreases $\delta c_g$ and $\delta c_\gamma$ in magnitude. Therefore this method of determining the charge of a very heavy fermion requires precise measurements of the Higgs couplings.

2. When more than one fermion contributes to eqs. (2) interpretation of the ratio in eq. (3) is not as straightforward. In the special case that all heavy fermions whose masses receive significant contributions from EW symmetry breaking have identical color and electric charges, the charges in eq. (2) factor out and eq. (3) still holds.

3. We may define

$$q^2 \equiv 2 \frac{\delta c_\gamma}{\delta c_g}.$$  

(4)
For a single color-triplet fermion this is just the square of the electric charge of the fermion. More generally this is an “average” of the squared charges of multiple fermions weighted by \( d\ln m/d\ln v \). The quantity \( q^2 \) provides a useful discriminant among and building guide for models of new physics.

In addition to heavy fermions we may also entertain the possibility of heavy scalars and vectors whose masses arise in part from EW symmetry breaking. Similarly to the fermion case, a scalar with mass-squared \( m_s^2(v) \) and a vector with mass-squared \( m_v^2(v) \) contribute

\[
\begin{align*}
\delta c_g &= \frac{1}{2} I(R_S) \frac{d \ln m_s}{d \ln v} A_S(x_S) - \frac{21}{2} I(R_V) \frac{d \ln m_v}{d \ln v} A_V(x_V) \\
\delta c_\gamma &= \frac{Q_s^2}{24} D(R_S) \frac{d \ln m_s}{d \ln v} A_S(x_S) - \frac{7}{8} Q_v^2 D(R_V) \frac{d \ln m_v}{d \ln v} A_V(x_V) .
\end{align*}
\]

(5)

\( R_S \) and \( Q_S \) are the color representation and charge of the scalar and \( A_S(x) = 3 [f(x) - x]/x^2 \), and \( R_V, Q_V \) and \( A_V(x) = [3(2x - 1)f(x) + 3x + 2x^2]/(7x^2) \) are the corresponding quantities for the vector. \( A_S \) and \( A_V \) both approach one for small arguments. Again for a single particle (scalar, fermion or vector) the discriminant \( \bar{q}^2 \) is simply \((4/3)(Q^2/C_2(R)) \). In the more general case of several particles the contribution of scalars to \( \delta c \) is a factor of 4 smaller than that of fermions of the same charges, while the contribution from vectors is more than 5 times larger. However, most models of EW symmetry breaking do not contain new colored vectors with EW symmetry breaking masses so that \( I(R_V) = 0 \), and electrically charged vectors are strongly constrained from precision EW measurements, usually requiring masses in the multi-TeV range.

As an example we consider a simple model in which the dominant contributions to \( \delta c_g \) and \( \delta c_\gamma \) stem from a vector-like colored heavy fermion. We determine the desired charges of this new fermion by consulting fits of \( \delta c_g \) and \( \delta c_\gamma \) to LHC data. Such fits have been performed by a number of groups\(^2\) with generally consistent results. For example, \(^2\) fit \( \delta c_g \) and \( \delta c_\gamma \) to the combined LHC and Tevatron cross section data assuming that the tree level couplings of the Higgs to SM particles maintain their SM values. The fit in Figure 1 of their paper indicates that current data somewhat prefer negative values for \( \delta c_\gamma \) and \( \delta c_g \), indicating that the heavy fermion mass should receive negative contributions from EW symmetry breaking. Furthermore, the fit shows a correlation between \( \delta c_\gamma \) and \( \delta c_g \). Although the current data is not highly constraining, it does hint at a ratio

\[
2 \frac{\delta c_\gamma}{\delta c_g} \equiv \bar{q}^2 \gtrsim 2 .
\]

(6)
For our example of a single fermion dominating the ratio this implies the electric charge of the fermion should satisfy

$$Q^2 \gtrsim \frac{3}{2} C_2(R) .$$

(7)

The quadratic Casimir for $SU(3)$ representations is bounded below by $C_2(R) \geq 4/3$ (with equality for a color triplet), and eq. (7) then forces the colored fermion to have charge $\gtrsim \sqrt{2}$. In the interest of keeping the electric charges as small as possible we choose the color-triplet representation: our new fermion is a “quark” with an exotic charge. The null results from experimental searches for fractionally charged heavy baryons or mesons suggest that the charges of any color triplet quarks should be quantized as

$$Q = \frac{2}{3} + \text{integer} .$$

(8)

The smallest charge greater than $\sqrt{2}$ consistent with eq. (8) is $Q = 5/3$. These charge assignments then lead to the prediction $q^2 = 25/9 \approx 2.78$.

We now present a minimal model for the couplings of this new quark. We describe all new fermions by left-handed Weyl spinors. We include a vector-like pair of $SU(2)$-singlet hypercharge $5/3$ quarks $\psi_S$ and $\bar{\psi}_S$. Renormalizable couplings of these fermions to the Higgs doublet require additional quark doublets $\Psi_D$ and $\bar{\Psi}_D$. The new fields then fill out $(SU(3),SU(2))_{U(1)}$ representations as

$$\psi_S = (3,1)_{5/3}, \quad \bar{\psi}_S = (\bar{3},1)_{-5/3}, \quad \Psi_D = (3,2)_{7/6}, \quad \bar{\Psi}_D = (\bar{3},2)_{-7/6} .$$

(9)

The gauge invariant mass terms and Higgs couplings of these new fields are then

$$- M_D \bar{\Psi}_D \Psi_D - M_S \bar{\psi}_S \psi_S - \sqrt{2} \lambda \bar{\Psi}_D H \psi_S - \sqrt{2} \lambda \bar{\psi}_S H^\dagger \Psi_D + \text{h.c.} ,$$

(10)

Bear in mind that bars on the fields are part of the field names (they do not correspond to complex conjugation) and the coupling constant $\lambda$ is unrelated to $\lambda$.

The mass matrix and Higgs couplings follow from the substitution $H = (v + h, 0)/\sqrt{2}$. Notice that the charge $2/3$ quark does not couple to the Higgs field $h$ and therefore does not contribute to $\delta c_g$ and $\delta c_\gamma$. There are two Dirac charge $5/3$ quarks which mix after electroweak symmetry breaking. Since they have the same color and electric charges eq. (3) applies and we confirm the prediction

$$2 \frac{\delta c_\gamma}{\delta c_g} = 2 \frac{\frac{5}{3}}{\frac{2}{3} \frac{4}{3}} = \frac{25}{9} .$$

(11)
Having fixed the charge from the discriminant $q^2$ we turn to the individual photon and gluon couplings. The contributions to $\delta c_\gamma$ allow us to further fix the fraction of the fermion masses arising from EW symmetry breaking. Only the charge $5/3$ quarks contribute and from eq. (2) we see that we need to compute

$$\sum \frac{d \ln m}{d \ln v} = \frac{d \ln \det M^\dagger M}{d \ln v^2}.$$ (12)

The charge $5/3$ mass matrix is

$$M_{5/3} = \begin{pmatrix} M_D & \lambda v \\ \bar{\lambda}v & M_S \end{pmatrix}$$ (13)

with determinant $\det M_{5/3} = (M_D M_S - \lambda \bar{\lambda} v^2) = M m$ where $M$ and $m$ are the masses of the two charge $5/3$ quarks. Putting these relations together we obtain (in the heavy mass limit $M, m \gg m_h$)

$$\delta c_\gamma = -\frac{\lambda \bar{\lambda} v^2}{Mm} \frac{25}{9}$$ (14)

This relation clearly exhibits the decoupling property, vanishing as we take the vectorial masses $M_D, M_S$ to infinity while holding the Yukawa couplings fixed. Also note that in the limit that $M_D \to \infty$ this becomes a classic see-saw, and upon integrating out the heavy state the system reduces exactly to the single fermion case we described at the beginning of the introduction.

As a numerical example consider $M_D = M_S = 900$ GeV and $\lambda = \bar{\lambda} = 1.2$. Then the charge $2/3$ quark has a mass of 900 GeV, while the two charge $5/3$ mass eigenstates have masses about $m \simeq 600$ GeV and $M \simeq 1.2$ TeV. The couplings $\delta c_\gamma \simeq -0.35, \delta c_g \simeq -0.25$ are then consistent with the latest LHC data.

We turn to a rough sketch of the collider phenomenology of the model. The masses of the three new vector-like quarks, two of charge $5/3$ and one of charge $2/3$, are determined by the free parameters $M_D, M_S, \lambda,$ and $\bar{\lambda}$. They must lie in the range of a few 100s of GeV to a few TeV in order to significantly affect the Higgs branching fraction to photons. Furthermore the structure of the mass matrices forces the charge $2/3$ quark mass (900 GeV in the example point) to lie between the charge $5/3$ masses.

At the LHC these new quarks can all be pair-produced with the usual QCD cross sections. To understand decays note that the only interactions we have introduced thus far are the gauge interactions and the Yukawa couplings to the Higgs in eq. (10). These interactions preserve a heavy quark baryon number under which only the new quarks are charged.
Therefore the lightest charge $5/3$ quark is stable and the heavier quarks decay to the lightest of the new quarks by emitting either $W^\pm$, $Z$ or $h$ bosons as shown in fig. 1. A significant contribution to $\delta c_\gamma$ requires sizeable EW splittings between the heavy quark masses so that the cascade decays between the heavy quarks produce on-shell $W$, $Z$ and $h$ particles.

If the lightest new quark were stable, new heavy charged hadrons would have been observed. Thus we must include interactions which allow the lightest charge $5/3$ quark to decay into SM particles. There is a unique renormalizable coupling of the new fermions to the SM fermions: the “Yukawa” coupling of the heavy $SU(2)$ doublet to the SM $SU(2)$ singlet hypercharge $-2/3$ quarks. Given the hierarchical pattern of Yukawa couplings between the different SM families and given strong constraints from flavor physics it is natural to expect that the mixing with first and second family quarks is very small, rendering it unimportant for LHC phenomenology. So we keep only the coupling to the top quark

$$\lambda_{\text{decay}} t^c H \Psi_D .$$

This coupling ties the heavy quark baryon number to ordinary baryon number and our heavy triplet quarks then have conventional baryon number $1/3$. Upon EW breaking this Yukawa interaction mixes the heavy charge $2/3$ quark in $\Psi_D$ with the top quark and allows the heavy quarks to decay to top and bottom quarks through the transitions indicated in fig. 1.

The cascade decays from the heaviest to the lightest of the new quarks via the gauge couplings and the large Higgs couplings are very fast. The further decay to SM quarks
depends on the arbitrary coupling $\lambda_{\text{decay}}$: the lightest charge $5/3$ quark may decay promptly, with a displaced vertex, or it may even be stable on collider time scales when $\lambda_{\text{decay}} \lesssim 10^{-8}$.

Different regimes for $\lambda_{\text{decay}}$ lead to varied phenomenologies. For the smallest couplings heavy quarks are long-lived leading to a rich system of exotic QCD bound states containing a heavy quark, including charge 2 mesons and charge 3 baryons. For the largest couplings the top quark mixes strongly with the exotic charge $2/3$ quark leading to significant modifications of the top quark couplings to the $W$ and $Z$ bosons. Since $b$ quarks do not have a corresponding partner to mix with the constraints from $R_b$ and $A_b$ are weaker.

We will briefly focus on modest couplings $10^{-6} \lesssim \lambda_{\text{decay}} \lesssim 10^{-1}$ with the lightest new quark decay being prompt yet still much slower than the decays of the heavier quarks. Then the heavier new quarks always decay down to the lightest new quark, which in turn decays via $W^+ t \rightarrow W^+ W^+ b$. Thus pair production of any of the heavy quarks leads to clear signatures with 4 to 8 $W$s and 2 $b$ jets, an example of which is shown in fig. 2.

Precision EW constraints on this model are not expected to be very severe. Contributions of the new fermions to precision observables arise at loop level and scale like $\delta_{\text{PEW}} \sim \lambda^2/(16\pi^2)(v^2/M^2)$ which we expect to be sufficiently small for most of parameter space. Also note that the contributions to the $S$ and $T$ parameters, which usually place the strongest constraints on new physics coupling to weak gauge bosons, are not enhanced by the square of the large charges of the new quarks.

The strongest lower bounds on the masses of the heavy quarks come from ATLAS and CMS searches for fourth family $B$ quarks which are assumed to decay as $B \rightarrow W^- t \rightarrow WWb$, and therefore $B\overline{B}$ production leads to the same final state as pair production of the lighter charge $5/3$ quark. ATLAS searches require the $B$ mass heavier than about 480 GeV\cite{17}, while CMS searches require a mass greater than 611 GeV\cite{18}. 

FIG. 2. Example heavy charge $5/3$ quark decay with six $W$s and a Higgs.
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