Fermion Mass Hierarchy and New Physics at the TeV Scale

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Abstract. In this talk, I present a new framework to understand the long-standing fermion mass hierarchy puzzle. We extend the Standard Model gauge symmetry by an extra local $U(1)_S$ symmetry, broken spontaneously at the electroweak scale. All the SM particles are singlet with respect to this $U(1)_S$. We also introduce additional flavor symmetries, $U(1)_{F_i}$'s, with flavon scalars $F_i$, as well as vectorlike quarks and leptons at the TeV scale. The flavon scalars have VEV in the TeV scale. Only the top quark has the usual dimension four Yukawa coupling. EW symmetry breaking to all other quarks and leptons are propagated through the messenger field, $S$ through their interactions involving the heavy vector-like fermions and $S$, as well as through their interactions involving the vector-like fermions and $F_i$. In addition the explaining the hierarchy of the charged fermion masses and mixings, the model has several interesting predictions for Higgs decays, flavor changing neutral current processes in the top and the b quark decays, decays of the new singlet scalars to the new $Z'$ boson, as well as productions of the new vectorlike quarks. These predictions can be tested at the LHC.

Keywords: Fermions, hierarchy, new physics, TeV scale

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INTRODUCTION

Fermion mass hierarchy is a long-standing problem in particle physics. The charged fermion masses vary by five orders of magnitude, while the quark mixing angles vary by almost two orders of magnitude. There are two main approaches to understand this puzzle [1, 2, 3, 4, 5]. This hierarchy is caused by physics at the high scale (GUT scale or the Planck scale: so called Froggatt-Nielsen type mechanism; or this is caused by some new physics at the TeV scale. In this work, I present a new model for this second approach with new physics at the TeV scale [6].

What are the new physics possibilities at the TeV scale? Supersymmetry is highly motivated, and predicts new superpartners and the Higgs boson at the TeV scale. Extra dimensions are somewhat motivated, and predicts new Kaluza-Klein excitations at the TeV scale. Extra $U(1)$ is somewhat string theory motivated, and predicts new gauge boson at the TeV scale. However these are all theory motivated. The experimental clues

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so far are that the charged fermion masses are highly hierarchial, quark mixing angles are hierarchial, and FCNC processes are strongly suppressed. The natural question is what sort of new physics can explain these, and can be observed at the LHC. In this talk, I present one such possibility.

In the SM, the Yukawa interactions of the fermions, in the mass basis, are parameterized by

$$L = y_d q_i d_R H + y_u q_i u_R \tilde{H} + h.c.$$  \hspace{1cm} (1)

with $m_{q_i} = y_{q_i} v$, where $v = < H >$. Note that $y_t \sim 1$, whereas the Yukawa couplings of all the light quarks and leptons, $y_b, y_c, y_s, y_d, y_u, y_e, y_{\mu}, y_{\tau}$ are $\ll 1$. Thus the top quark is directly connected to the EW symmetry breaking sector, and has dimension 4 Yukawa interactions. The lighter quarks are probably not directly connected to the EW symmetry breaking sector. They may be connected via some messenger fields.

We know that the FCNC interactions among the quarks are highly suppressed. This hints at the existence of some sort of flavor symmetry. Furthermore, if we let all the SM fermions except $q_3L, u_{3R}$ and $H$ carry nonzero flavor charges, then the dimension 4 Yukawa couplings for the light quarks with $H$ will be prevented. These flavor symmetries need to be global, and have to be spontaneously broken at the TeV scale. What sort of fields in addition to the SM we need to achieve this scenario? We shall see that one possibility is to have vectorlike quarks, $Q$ and leptons at the TeV scale, and additional flavor symmetries, $U_i(1)_{F_i}$. Again, since the light quarks and leptons are not directly connected to the EW symmetry breaking scale, we need a messenger field to achieve this, and a SM singlet complex scalar field with an extra $U(1)_S$ local symmetry will serve our purpose. Thus the new physics in our scenario will involve $Q, S$ and $Z'$.  

**MODEL AND FORMALISM**

We extend the gauge symmetry of the SM model by a $U(1)_S$ local symmetry and $U_i(1)_{F_i}$ global symmetries. All of the SM fermions are neutral with respect to $U(1)_S$, while all of the SM fermions apart from the third generation quark doublet $q_{3L}$ and right-handed top $u_{3R}$ are charged under the global $U_i(1)_{F_i}$. We introduce a complex scalar field $S$ which has charge 1 under $U(1)_S$, is neutral under $U_i(1)_{F_i}$, and is a SM singlet. We also introduce complex scalar fields $F_i$, the “flavons”, which have charges under $U_i(1)_{F_i}$, are neutral under $U(1)_S$, and are SM singlets. The Higgs field $H$ is taken as neutral under $U(1)_S$ and $U_i(1)_{F_i}$. We assume that the $U_i(1)_{F_i}$ charges of the SM fermions are such that only the top quark has an allowed dimension 4 Yukawa interaction.

The $S$ field acquires a vev at the EW scale that spontaneously breaks the $U(1)_S$ symmetry. The pseudoscalar component of $S$ is eaten to give mass to the $U(1)_S$ gauge boson $Z'$. The field $S$ acts as a messenger to both the flavor symmetry breaking and EW symmetry breaking. The $U_i(1)_{F_i}$ symmetries are broken by the vev of the flavon scalar fields, $F_i$ at the TeV scale. There are additional vectorlike fermions at the TeV scale charged under both $U(1)_S$ and $U_i(1)_{F_i}$.

In this framework, the Yukawa interactions of the light fermions, after integrating out the heavy vectorlike fermions appear as higher dimensional operators in a hierarchial
pattern given by
\[
\left( \frac{S^\dagger S}{M^2} \right)^n \left( \frac{F_i}{M} \right)^{n_1} \left( \frac{F_j}{M} \right)^{n_2} f_{ij} q_i L d_i R H,
\]
with similar expressions for the up sector. The observed fermion mass hierarchy and mixings are reproduced in powers of \( \varepsilon \)
\[
\varepsilon = \frac{< s >}{M} \sim \frac{1}{7},
\]
which we call the "little" hierarchy. We can absorb the \( F/M \) dependence into field-dependent dimensionless complex couplings \( h_{ij} \), where \( i, j \) are generation labels. The values of these couplings we will then take to be of order 1.

In the model we propose, the observed fermions mass hierarchy is generated from the following low energy effective interactions:
\[
\mathcal{L}^{Yuk} = h_{33}^u \overline{q}_3 L u_3 R \tilde{H} + \left( \frac{S^\dagger S}{M^2} \right)^2 \left( h_{22}^d \overline{q}_2 L d_2 R H + h_{23}^d \overline{q}_2 L d_3 R H + h_{32}^d \overline{q}_3 L d_2 R H \right)
+ h_{12}^u \overline{q}_1 L u_2 R \tilde{H} + h_{21}^u \overline{q}_2 L u_1 R \tilde{H} + h_{13}^u \overline{q}_1 L u_3 R \tilde{H} + h_{31}^u \overline{q}_3 L u_1 R \tilde{H}
+ \left( \frac{S^\dagger S}{M^2} \right)^3 \left( h_{11}^u \overline{q}_1 L u_1 R \tilde{H} + h_{12}^d \overline{q}_1 L d_1 R H + h_{13}^d \overline{q}_1 L d_3 R H + h_{21}^d \overline{q}_2 L d_1 R H
+ h_{31}^d \overline{q}_3 L d_1 R H \right) + h.c.
\]
where all the couplings \( h_{ij} \) are assumed to be of order 1.

Note that the above interactions are very similar to those proposed in reference [7, 8], except our interactions involve suppression by powers of \( \left( \frac{S^\dagger S}{M^2} \right) \), instead of \( \left( \frac{H^\dagger H}{M^2} \right) \).

**Fit to Fermion Masses and CKM Mixing**

The gauge symmetry of our model is the usual SM symmetry, plus an additional \( U(1)_S \) symmetry. The SM symmetry is broken spontaneously by the usual Higgs doublet, \( H \) at the EW scale. We assume that the extra \( U(1)_S \) symmetry is also broken spontaneously at the EW scale by a SM singlet complex scalar field, \( S \). The pseudoscalar part of the complex scalar field, \( S \) is absorbed by the \( Z' \) to get its mass. Thus after symmetry breaking, the remaining scalar fields are \( h \) and \( s \). Parameterizing the Higgs doublet and singlet in the unitary gauge as
\[
H = \left( \frac{0}{\sqrt{2}} + v \right) \quad S = \left( \frac{s^0}{\sqrt{2}} + v_s \right),
\]

with $v \approx 174$ GeV, and defining an additional small parameter

$$\beta \equiv \frac{v}{M},$$

we obtain, from Eqs. (2-4) the following mass matrices for the up and down quark sector:

$$M_u = \left( \begin{array}{ccc} h_{11}^u v^6 & h_{12}^u v^4 & h_{13}^u v^4 \\ h_{21}^u v^4 & h_{22}^u v^2 & h_{23}^u v^2 \\ h_{31}^u v^4 & h_{32}^u v^2 & h_{33}^u v^2 \end{array} \right) \nu,$$

$$M_d = \left( \begin{array}{ccc} h_{11}^d v^6 & h_{12}^d v^4 & h_{13}^d v^4 \\ h_{21}^d v^4 & h_{22}^d v^2 & h_{23}^d v^2 \\ h_{31}^d v^4 & h_{32}^d v^2 & h_{33}^d v^2 \end{array} \right) \nu .$$

The charged lepton mass matrix is obtained from $M_d$ by replacing the couplings $h_{ij}$ appropriately. Note that these mass matrices are the same as in Ref. [7], and as was shown there, good fits to the quark and charged lepton masses, as well as the CKM mixing angles are obtained by choosing $\varepsilon \sim 0.15$, and all the couplings $h_{ij}$ of order one. To leading order in $\varepsilon$, the fermion masses are given by

$$(m_t, m_c, m_u) \approx (|h_{13}^u|, |h_{22}|, |h_{11} - (h_{12} h_{21} / h_{22})|) \varepsilon,$$

$$(m_y, m_s, m_d) \approx (|h_{33}^d|, |h_{22}|, |h_{11}|) \varepsilon,$$

$$(m_\tau, m_\mu, m_e) \approx (|h_{33}^e|, |h_{22}|, |h_{11}|) \varepsilon,$$

while the quark mixing angles are

$$|V_{us}| \approx \left| \frac{h_{12}^d}{h_{22}^d} - \frac{h_{12}^u}{h_{22}^u} \right| \varepsilon^2,$$

$$|V_{cb}| \approx \left| \frac{h_{23}^d}{h_{33}^d} - \frac{h_{23}^u}{h_{33}^u} \right| \varepsilon^2,$$

$$|V_{ub}| \approx \left| \frac{h_{13}^d}{h_{33}^d} - \frac{h_{12}^d h_{23}^d}{h_{22}^d h_{33}^d} - \frac{h_{13}^u}{h_{33}^u} \right| \varepsilon^4 .$$

### Yukawa Interactions and FCNC

Our model has flavor changing neutral current interactions in the Yukawa sector. Using Eqs.(1-4), the Yukawa interaction matrices $Y_u^h$, $Y_d^h$, $Y_u^s$, $Y_d^s$ for the up and down sector, for $h^0$ and $s^0$ fields are obtained to be

$$\sqrt{2} Y_u^h = \left( \begin{array}{ccc} h_{11}^u v^6 & h_{12}^u v^4 & h_{13}^u v^4 \\ h_{21}^u v^4 & h_{22}^u v^2 & h_{23}^u v^2 \\ h_{31}^u v^4 & h_{32}^u v^2 & h_{33}^u v^2 \end{array} \right), \quad \sqrt{2} Y_d^h = \left( \begin{array}{ccc} h_{11}^d v^6 & h_{12}^d v^4 & h_{13}^d v^4 \\ h_{21}^d v^4 & h_{22}^d v^2 & h_{23}^d v^2 \\ h_{31}^d v^4 & h_{32}^d v^2 & h_{33}^d v^2 \end{array} \right),$$

with the charged lepton Yukawa coupling matrix $Y_\ell$ obtained from $Y_d$ by replacing $h_{ij} \rightarrow h_{ij}^\ell$. 

$$\sqrt{2} Y_u^s = \left( \begin{array}{ccc} h_{11}^s v^6 & h_{12}^s v^4 & h_{13}^s v^4 \\ h_{21}^s v^4 & h_{22}^s v^2 & h_{23}^s v^2 \\ h_{31}^s v^4 & h_{32}^s v^2 & h_{33}^s v^2 \end{array} \right) .$$
\[ \sqrt{2} Y_u = \begin{pmatrix} 6h_{11}u^5 \beta & 4h_{12}u^3 \beta & 4h_{13}u^3 \beta \\ 4h_{21}u^3 \beta & 2h_{22}u e \beta & 2h_{23}u e \beta \\ 4h_{31}u^3 \beta & 2h_{32}u e \beta & 0 \end{pmatrix}, \] (9)

\[ \sqrt{2} Y_d = \begin{pmatrix} 6h_{11}d^5 \beta & 6h_{12}d^5 \beta & 6h_{13}d^5 \beta \\ 6h_{21}d^5 \beta & 4h_{22}d^5 \beta & 4h_{23}d^5 \beta \\ 6h_{31}d^5 \beta & 4h_{32}d^3 \beta & 2h_{33}d^3 \beta \end{pmatrix}, \] (10)

with the charged lepton Yukawa coupling matrix \( Y_\ell \) obtained from \( Y_d \) by replacing \( h_{ij}^d \rightarrow h_{ij}^\ell \).

There are several important features that distinguish our model from the proposal of Refs. [7, 8, 9]. i) Note, from Eqs. (5) and (8), in our model, the Yukawa couplings of \( h \) to the SM fermions are exactly the same as in the SM. This is because the fermion mass hierarchy in our model is arising from \( \left( S^\dagger S \right)^M \). This is a distinguishing feature of our model from that proposed in [7, 8] where the Yukawa couplings of \( h \) are flavor dependent, because the hierarchy there arises from \( \left( H^\dagger H \right)^M \). ii) In our model, we have an additional singlet Higgs boson whose coupling to the SM fermions are flavor dependent as given in Eq. (9, 10). Again, this is because the hierarchy in our model arises from \( \left( S^\dagger S \right)^M \). In particular, \( s^0 \) does not couple to the top quark, and its dominant fermionic coupling is to the bottom quark. This will have interesting phenomenological implications for the Higgs searches at the LHC. iii) We note from Eq. (5-8) that the mass matrices and the corresponding Yukawa coupling matrices for \( h \) are proportional as in the SM. Thus there are no flavor changing Yukawa interactions mediated by \( h \). However, this is not true for the Yukawa interactions of the singlet Higgs as can be seen from Eqs. (5) and (9, 10). Thus \( s \) exchange will lead to flavor violation in the neutral Higgs interactions.

**Higgs Sector and Extra \( Z' \)**

The Higgs potential of our model, consistent with the SM and the extra \( U(1)_S \) symmetry, can be written as

\[ V(H, S) = -\mu_H^2 (H^\dagger H) - \mu_S^2 (S^\dagger S) + \lambda_H (H^\dagger H)^2 + \lambda_S (S^\dagger S)^2 + \lambda_{HS}(H^\dagger H)(S^\dagger S). \] (11)

Note that after absorbing the three components of \( H \) in \( W^\pm \) and \( Z \), and the pseudoscalar component of \( S \) in \( Z' \), we are left with only two scalar Higgs, \( h^0 \) and \( s^0 \). The squared mass matrix in the \((h^0, s^0)\) basis is given by

\[ M^2 = 2v^2 \begin{pmatrix} 2\lambda_H & \lambda_{HS}\alpha \\ \lambda_{HS}\alpha & 2\lambda_S\alpha^2 \end{pmatrix}, \] (12)

where \( \alpha = v_s/v \).
The mass eigenstates $h$ and $s$ can be written as
\begin{align*}
h^0 &= h \cos \theta + s \sin \theta, \\
{s^0} &= -h \sin \theta + s \cos \theta,
\end{align*}
where $\theta$ is the mixing angle in the Higgs sector.

In the Yukawa interactions discussed above, as well as in the gauge interactions involving the Higgs fields, the fields appearing are $h^0$ and $s^0$, and these can be expressed in terms of $h$ and $s$ using Eq. (13).

The mass of the $Z'$ gauge boson is given by
\begin{equation}
m_{Z'}^2 = 2 g_E^2 v_s^2 \tag{14}
\end{equation}

Note that the $Z'$ does not couple to any SM particles directly. Its coupling with the neutral scalar Higgs $h$ ($Z'h h$ coupling) is also zero. The $Z'$ coupling to the SM particles will be only via dimension six or higher operators. Such couplings are generated by the vectorlike fermions in the model.

**PHENOMENOLOGICAL IMPLICATIONS: CONSTRAINTS, PREDICTIONS AND NEW PHYSICS SIGNALS**

**Constraint on the mass of $s$:** Experiments at LEP2 have set a lower limit of 114.4 GeV for the mass of the SM Higgs boson. This is due to the nonobservation of the Higgs signal from the associated production $e^+ e^- \to Zh$. In our model, since the singlet Higgs can mix with the doublet $h$, there will be a limit for $m_s$ depending on the value of the mixing angle, $\theta$. For $\cos^2 \theta \geq 0.25$, the bound of 114.4 applies also for $m_s$ [10]. However, $s$ can be lighter if the mixing is small.

**Constraint on the mass of the $Z'$:** We have assumed that the extra $U(1)$ symmetry in our model is spontaneously broken at the EW scale. But the corresponding gauge coupling, $g_E$ is arbitrary and hence the mass of $Z'$ is not determined in our model. However, very accurately measured $Z$ properties at LEP1 put a constraint on the $Z - Z'$ mixing to be $\sim 10^{-3}$ or smaller [11, 12]. In our model, the $Z'$ does not couple to any SM particle directly; $Z - Z'$ mixing can take place at the one loop level with the new vectorlike fermions in the loop. The mixing angle is
\begin{equation}
\theta_{ZZ'} \sim \frac{g_Z g_E}{16\pi^2} \left(\frac{m_Z}{M}\right)^2, \tag{15}
\end{equation}
where $M$ is the mass of the vectorlike fermions with masses in the TeV scale. Even with $g_E \sim 1$, we get $\theta_{ZZ'} \sim 10^{-4}$ or less. Thus there is no significant bound for the mass of this $Z'$ from the LEP1 [13].

**Higgs signals:** As can be seen from Eq. (8), the couplings of the doublet Higgs $h$ to the SM fermions are identical to that in the SM, whereas the couplings of the singlet Higgs are flavor dependent. In particular, the singlet Higgs $s$ does not couple to the top quark, whereas its coupling to $(b, \tau; c, s, \mu; u, d, e)$ involve the flavor dependent factors $2, 2; 2, 4, 4; 6, 6, 6)$ respectively. This is, of course, in the limit of zero mixing between
$h$ and $s$. Including the mixing, these factors will be modified by the appropriate mixing factors. Thus our model will be distinguished from the SM by the fact that the Higgs couplings, in general, will be fermion flavor dependent.

**Higgs decays:** The couplings of the Higgs bosons $h$ and $s$ to the fermions and the gauge bosons can be obtained from Eqns. (8) and (9, 10). Because of the flavor dependency of the couplings of $s_0$ (and hence for both $h$ and $s$ via mixing) to the fermions, the branching ratios (BR) for $h$ to various final states are altered substantially from those in the SM. These branching ratios (BR) for $h$ to the various final states are shown in Figs. 1, 2 for the values of the mixing angle, $\theta = 0^\circ$ and $26^\circ$ [14].

For $\theta = 0$, these BR’s are the same as for the SM. Note that for $\theta = 26^\circ$, the $gg$ and $\gamma\gamma$ the BR’s are enhanced substantially compared to the SM. This is due to drastic reduction for the $b\bar{b}$ mode due the almost cancelation in the corresponding coupling In particular, for $\theta = 26^\circ$, the effect is quite dramatic. For a light Higgs ($m_h$ around 115 GeV), the usually dominant $b\bar{b}$ mode is highly suppressed and the $\gamma\gamma$ mode is enhanced by a factor of almost 10 compared to the SM. This is to be contrasted with the proposal of Refs. [7, 8] in which the $h \rightarrow \gamma\gamma$ mode is reduced by about a factor of 10. Thus the Higgs signal in this mode for a Higgs mass of $\sim 114 - 140$ GeV gets a big enhancement making its potential discovery via this mode much more favorable at the LHC. Such a signal may be observable at the Tevatron for a Higgs mass $\sim 114$ GeV as the luminosity accumulates, but would require about 10 fb$^{-1}$ of data [15].

Another interesting effect is the Higgs signal via the $WW^*$ for the light higgs. In the SM, this mode becomes important for the Tevatron search staring at $m_h \sim 135$ GeV, where the BR to $WW^*$ is approximate equal to that of $b\bar{b}$. Currently Tevatron Run2 experiments have excluded SM Higgs mass in the range of 160 to 170 GeV (where the BR to $WW^*$ is around 100 percent) for this mode. In our model, for $\theta = 26^\circ$ for example, note that this cross over between the $WW^*$ mode and the $b\bar{b}$ mode takes place sooner

![Higgs Branching Ratios, $\theta=0$](image-url)

**FIGURE 1.** Branching ratio of $h \rightarrow 2x$. Here $\alpha = 1$. 
than 135 GeV. Thus the Tevatron will be more sensitive to lower mass range than in the SM, and will be able to exclude mass ranges much smaller than 160 GeV.

**Top quark physics:** In the SM, \( t \to ch \) mode is severely suppressed with a BR \( \sim 10^{-14} \) [16]. In our model, as can be seen from Eqs.(8) and (9, 10), although \( t \to ch \) is zero at tree level, we have a large coupling for \( t \to cs \sim 2\varepsilon\beta \). This gives rise to significant BR for the \( t \to cs \) mode for a Higgs mass of up to about 150 GeV. If the mixing between the \( h \) and \( s \) is substantial, both decay modes, \( t \to cs \) and \( t \to ch \) will have BR \( \sim 10^{-3} \). With a very large \( t\overline{t} \) cross section, \( \sigma_{t\overline{t}} \sim 10^3 \) pb at the LHC, this can be a major discovery mode for higgs bosons at the LHC. Observation of signals for two different Higgs masses will also show clear evidence for new physics beyond the SM.

**Z’ physics:** Our model has a \( Z’ \) boson in the EW scale from the spontaneous breaking of the extra \( U(1)_S \) symmetry. As discussed before, since the \( Z-Z’ \) mixing is very small \( \sim 10^{-4} \) or less, its mass is not constrained by the very accurately measured Z properties at LEP. Its mass can be as low as few GeV from the existing constraints. This \( Z’ \) does not couple to the SM particles with dimension 4 operators. It does couple to \( s \) at tree level via the \( sZ’Z’ \) interaction. Thus it can be produced via the decay of \( s \) (or \( h \) if there is a substantial mixing between \( h \) and \( s \)). This gives an interesting signal for the Higgs decays, \( s \to Z’Z’ \), \( h \to Z’Z’ \) if allowed kinematically.

\( B_s^0 \to \mu^+ \mu^- \): In our model this decay gets a contribution from an FCNC interaction mediated by \( s \)-exchange. The amplitude for this decay is \( A \sim 4h_{22}^d h_{22}^f \varepsilon^6 \beta^2 \). Taking \( \beta \sim \varepsilon, A \sim 4h_{22}^d h_{22}^f \varepsilon^8 \), and with the couplings \( h_{22}^d, h_{22}^f \sim 1 \), we obtain the branching ratio, \( BR(B_s^0 \to \mu^+ \mu^-) \sim 10^{-9} \). Current experimental limit for this BR is \( 4.7 \times 10^{-8} \) [11], and thus this decay could be observed soon at the Tevatron as the luminosity accumulates.

**Vectorlike fermions, productions and decays:** Our model requires vectorlike quarks and leptons, both \( SU(2) \) doublets, \( Q_i \) and singlets \( U_i \) and \( D_i \), with masses at the TeV scale. These will be pair produced at high energy hadron colliders via strong interaction.
For example, for a 1 TeV vectorlike quark, the production cross section at the LHC is $\sim 60$ fb [17]. We need several such vectorlike quarks for our model. So the total production cross section will be few hundred fb. These will decay to the light quarks of the same electric charge and Higgs bosons ($h$ or $s$): $Q \rightarrow qh, qs$. Thus the signal will be two high $p_T$ jets together with the final states arising from the Higgs decay. For a heavy Higgs, in the golden mode ($h \rightarrow ZZ, s \rightarrow ZZ$, this will give rise to two high $p_T$ jets plus four $Z$ bosons. In the case of a light $Z'$, the final state signal will be two high $p_T$ jets plus 8 charged leptons in the final state (with each lepton pair having the invariant mass of the $Z'$).

A CONCRETE MODEL

We have constructed a concrete model giving rise to the phenomenological Lagrangian. In addition to the SM, the model has a $U(1)_S$ local symmetry, and the $U_i(1)_{F_i}$ ($i = 1, 2, 3$) global symmetries. The global symmetries are slightly broken explicitly in the Higgs potential so that there are no unwanted Goldstone bosons. In addition to the SM fermions, the model has a complex scalar, $S$, the flavon fields $F_i$’s, and several vector-like quarks, both weak doublets and weak singlets. The details of their charge assignments under these symmetries, and how one obtains the interaction Lagrangian can be found in [6].

CONCLUSIONS

We have presented a proposal in which only the top quark obtains its mass from the Yukawa interaction with the SM Higgs boson via dimension four operators. All the other quarks receive their masses from operators of dimension six or higher involving a complex scalar Higgs $S$ whose vev is at the EW scale. The successive hierarchy of light quark masses is generated via the expansion parameter $\left( \frac{S^\dagger S}{M^2} \right) \sim \epsilon^2$, where $\epsilon \equiv \frac{v_s}{M} \sim 0.15$. All the couplings of the higher dimensional operators are of order one. We are able to generate the appropriate hierarchy of fermion masses with this small parameter $\epsilon$. Since $v_s$ is at the EW scale, the physics of the new scale, $M$ is at the TeV. Because of the new degree of freedom at the EW scale, we have an EW singlet neutral scalar $s$, which gives rise to interesting new physics signals which can be tested at the LHC and at the Tevatron. There are new scenarios for the Higgs decays and the top quark physics. The model has a light $Z'$ which can be produced via the Higgs decays at the LHC, and can give rise invisible Higgs decays, displaced vertices for the $Z'$ decays, or multilepton final states arise from the $Z'$ decays, depending on the mass and lifetime of the $Z'$. We have presented a model in which an effective interaction given in Eq. (1) can be realized. This requires the existence of vectorlike quarks and leptons, both EW doublets and singlets, at the TeV scale. These can be probed at the LHC. Their decays give rise to final states with 4 $Z$’s or 4 $Z'$’s and interesting new physics signals at the LHC.
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