Does Supersymmetry Require Two Higgs Doublets?

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We discuss a new class of low energy supersymmetric models in which the Higgs sector includes a single doublet, for example $H_u$, but not $H_d$. Chiral gauge anomalies are canceled against new electroweak-charged states. We discuss the main challenges in building such models, and present several models where these issues are addressed. The resulting phenomenology can be distinguished from that of the MSSM in a number of ways, most notably in physics related to down-type quarks and charged leptons. As a first step toward a chiral Higgs sector, we discuss the scenario of an inert $H_d$ doublet. We show that a UV completion of such model naturally includes dark matter with novel, flavorful couplings to SM quarks.

I. INTRODUCTION

In the Minimal Supersymmetric Standard Model (MSSM), the Higgs sector consists of a vector-like pair of doublets: $H_u$ and $H_d$ with hypercharges $1/2$ and $-1/2$, respectively. Virtually all the literature of low energy supersymmetry is based on this field content and on extensions thereof.

The need for both doublets can be justified by two arguments. The first argument is that a single chiral doublet of Higgsinos would suffer from gauge (and Witten) anomalies; the second is that holomorphy prevents the up(down)-type Higgs from having supersymmetric Yukawa couplings to down(up)-type fermions. Both these arguments can be challenged: anomaly cancellation can potentially be achieved with other (perhaps chiral) matter content, and as for holomorphy, one should realize that it is in force insofar as supersymmetry is not broken. Eventually, non-supersymmetric couplings of up-type Higgs to down-type fermions will be generated at some scale. This suggests that it may be possible to build supersymmetric models which do not have two vectorlike Higgs doublets.

In this note, we attempt to produce models where the Higgs sector is chiral, i.e., the model includes the chiral superfield $H_u$, but it does not include a field with the quantum numbers of $H_d$. Nevertheless, these models will be anomaly-free and will have large enough masses for down-type quarks and charged leptons. Such models have certain very attractive features, most notably the absence of the term $\mu H_u H_d$, thereby potentially solving the $\mu$-problem and explaining why the Higgs is light.

The main difficulty of a chiral Higgs sector is that in the absence of $H_d$, the Higgsino cannot acquire a mass until electroweak symmetry is broken. Furthermore, to cancel anomalies previously canceled by $H_d$, we will have to introduce new fields. The new fields must be chiral too, if they are to cancel the anomalies, but they must be given adequately large masses in order for the model to be phenomenologically viable. These requirements are challenging for model-building. Nevertheless, we show that models can be built, at least as effective field theories, where all anomalies are canceled, and the spectrum is phenomenologically viable.

As a first step toward a chiral Higgs sector, we will present a model with both $H_u$ and $H_d$, where $H_d$ does not couple to quark and lepton superfields at all. In this model, for which we also provide an ultraviolet completion, down-type quarks and charged leptons acquire masses without involving any component fields of $H_d$ (as opposed to $H_u$). Once we have established the possibility of such an inert $H_d$, which plays no role in (s)quark and (s)lepton phenomenology, we proceed to consider scenarios of a fully chiral Higgs sector, where $H_d$ is entirely absent from the theory. These models face new problems which we discuss in detail.

We analyze one such model in detail, where a single SM Higgs doublet is embedded in a chiral fourth generation. We show that this model is phenomenologically viable, and discuss some consequences. Next, we present
more examples of Higgs sectors which are chiral, yet fully massive. We close with a discussion of future directions.

II. DOWN-TYPE MASSES WITHOUT A
DOWN-TYPE HIGGS

In the MSSM, the Higgs doublets couple to quarks and leptons only via the supersymmetry-preserving terms

$$d^2\theta \left( Y_{uij} H_u Q_i \bar{u}_j + Y_{dij} H_d Q_i \bar{d}_j + Y_{eij} H_d L_i \bar{\ell}_j \right). \quad (1)$$

In particular, there is no tree-level coupling between $H_u$ and down-type quarks. However, in any extension of the MSSM, additional higher dimensional operators can be generated by new degrees of freedom at a scale $M$. These would generically include the terms

$$d^4\theta \frac{X^+}{M^2} \left( y'_{uij} H_u^i Q_i \bar{u}_j + y'_{dij} H_d^i Q_i \bar{d}_j + y'_{eij} H_u^i L_i \bar{\ell}_j \right), \quad (2)$$

where $X = F_X \theta^2$ parameterizes supersymmetry breaking. Such operators have been mentioned in [3], and also in [4] (where they arise by integrating out a heavy pair of Higgs doublets). Their presence is equivalent to having non-holomorphic terms in the superpotential, e.g.,

$$d^2\theta \int d^2\theta \frac{X^+}{M^2} \left( H_u^i Q \bar{d} \right) \equiv \left( \frac{F_X}{M^2} \right) \int d^2\theta \left( H_u^i Q \bar{d} \right). \quad (3)$$

This is not surprising, since the theory is indeed explicitly supersymmetry-violating. Effectively, the theory now includes “wrong-Higgs” Yukawa couplings, e.g., between the up-type Higgs and down-type fermions [3]. Such terms ostensibly induce hard supersymmetry-breaking in the low energy Lagrangian, but being inversely proportional to the cutoff $M$, they do not reintroduce the hierarchy problem. The resulting mass matrix of the down-type quarks is

$$m_d = y'_{d} v_u \frac{F_X}{M^2} + Y_d v_d \quad (4)$$

Consider a limiting scenario where $Y_u = 0$. In that case, $H_d$ becomes “inert”, i.e., it does not couple to SM quarks and leptons at tree-level. The down-type masses are generated purely by the higher dimensional couplings to $H_u$. The phenomenology of an inert $H_d$ doublet is different from that of the MSSM in several ways. For example, since the masses of the bottom and the tau are decoupled from $v_u$, $\tan \beta$ may be very large ($v_u \ll v_\tau$), without being ruled out by perturbativity (see [2] for a scenario with a similar feature).

Another distinctive feature of an inert $H_d$ scenario would be that the Higgs decay rate to $b\bar{b}$ is $1/\tan^2 \beta$ times its MSSM value. Essentially, $H_u$ becomes SM-like, while $H_d$ decouples, as far as low momentum physics is concerned.

Last, the operators in Eq. (2) induce only interactions with a Higgs scalar but never with Higgsinos. This is a consequence of the non-holomorphy in Eq. (3). It may have a significant effect on cascade decays, especially those which involve third generation particles. In the MSSM, such cascades are dominated by Higgsinos (in the form of charginos and neutralinos), since these couple strongly to the third generation. In the inert Higgs model, such contributions are very suppressed. Cascade decays can therefore be used to distinguish between the MSSM and an inert $H_d$ scenario.

A UV Completion

It is possible to generate the operators in Eq. (2) at one loop. As an interesting example, consider adding to the MSSM the superfields

$$S_{i}(1,1)_{0}, \quad T_{i}(1,1)_{0}, \quad Q'(3,2)_{1/6}, \quad b'(3,1)_{-1/3}, \quad (5)$$

along with their vectorlike counterparts ($\overline{S}_i, \overline{T}_i, \overline{Q}', \overline{b}'$), where the index $i$ runs over three copies, and the numbers denote the representation under the SM gauge group. The superpotential is taken to be

$$W \supset m_S \overline{S}_i + m_T \overline{T}_i + m_Q \overline{Q}' + m_b \overline{b}' + \lambda_{ij} \overline{S}_i T_j + \lambda_S S_i Q_l \overline{Q}' + \lambda_T T_i b_l \overline{d}_i + H_u \overline{Q}' b'. \quad (6)$$

At one loop, an effective coupling of the form

$$y'_{d} \left( \frac{X^+}{M^2} \right) H_u^{i} Q \bar{d} \quad (7)$$

is generated (see Fig. [1]), where

$$(y'_{d})_{ij} \sim \lambda_{ij} \lambda_S \lambda_T / 16\pi^2, \quad (8)$$

and where the scale $M$ is given by a combination of the mass parameters in Eq. (6). The charged lepton Yukawa couplings may be generated in a similar way. There are no flavor problems, since all the terms in Eq. (6) are flavor universal, excepting the $\lambda_{ij}$ coupling, which generates the entire down-type quark flavor structure. Therefore this setting is minimally flavor violating [5] by construction.
that it would be dark matter. Note that we may choose it to be one of the neutral even. This renders the lightest odd particle stable, and it is flavor-blind. Of the literature, where such couplings are assumed to be symmetry breaking sector. This is in contrast to most of the new fields which are odd, whereas the MSSM fields are superpotential \((6)\) has a new parity. Under the new par-

Another interesting feature of this model is that the superpotential \([6]\) has a new parity. Under the new para-

In conclusion, the inert Higgs scenario can be spec-

III. A MIRROR FOURTH GENERATION WITH A CHIRAL HIGGS

Having shown that the \(H_d\) superfield is not necessary for giving mass to the down-type fermions, we proceed to the more radical possibility, namely, eliminating it from the spectrum altogether. This is not viable by itself, since without \(H_d\) the theory is anomalous. However, including \(H_d\) in the spectrum is not the only way to cancel the anomalies due to \(H_u\).

Let us try to replace the MSSM Higgs sector

\[ H_u(1,2)_\frac{1}{2}, \quad H_d(1,2)_{-\frac{1}{2}} \]  

with a new set of fields which is chiral, and thus free of the \(\mu\)-problem. Perhaps the most straightforward way to do this (although not necessarily the most minimal) is to identify \(H_u\) with a lepton superfield \(\mathcal{L}\) of a mirror chiral fourth generation:

\[ \mathcal{Q}'(3,2)_{\frac{2}{3}}, L'(1,2)_{\frac{1}{2}}, \mathcal{T}'(1,1)_{-1}. \]

A similar idea was pursued in \([7]\) in the context of low scale gravity mediation and large extra dimensions.

In order for the model to be fully chiral, we must forbid mixing between the fourth generation, which is the new Higgs sector, and the first three generations

\[ Q_i(3,2)_{\frac{1}{3}}, \bar{u}_i(3,1)_{-\frac{1}{3}}, \bar{d}_i(3,1)_{\frac{1}{3}}, L_i(1,2)_{-\frac{1}{2}}, \bar{T}_i(1,1). \]

Note that such mixing is severely constrained by flavor physics in any case. In order to do this, we impose a \(Z_2\), under which only the SM generations are odd. In fact, this is a natural extension of the MSSM \(R\)-parity: the three generations of sfermions (matter sector) are odd, whereas the new scalars, which include also \(H_u\) (Higgs sector), are even. With these \(R\)-parity assignments we may still have Yukawa couplings between the up-type Higgs and the first three generations; the up-

We must still provide masses to the other fields of the fourth generation. The new mirror quarks may be given mass via the terms

\[ y_{\nu}^* \int d^2 \theta \mathcal{Q}' H_u + y_{\nu'} \int d^4 \theta X^+ H_u^\dagger \mathcal{Q}' t'. \]  

The \(t'\) mass is then of order \((F_X/M^2) \nu\). Direct collider searches at the Tevatron already place a bound on new quark masses of \(m_{q'} \gtrsim 350\) GeV. Therefore we must set \(F_X \sim M^2\), and the (unspecified) UV completion is required to be such that the \(y_{\nu'}\) coupling is of order 1.

So far, the model conserves a “4th generation baryon number” \(B'\), so that either \(b'\) or \(t'\) is stable. We prevent this by introducing the term

\[ \lambda \int d^2 \theta (b' \tau \bar{t}), \]  

such that the new quarks decay via \(\tau \bar{t}\) or \(\tau t\). This term introduces (non-minimal) flavor violation, but it does not conflict with existing experimental data, since it only involves the relatively poorly measured top and tau.
Another term allowed by $R$-parity is $Q_3b \tilde{b}$, but we must forbid it so that the $b'$ would not mediate fast proton decay. This can be done using discrete symmetries, such as “baryon parity”, under which all the quark fields (including the fourth generation) are odd while other fields are even.

So far, the Higgsinos and the $\tau'$ fermion are yet to be given mass. A superpotential term of the form $H_u H_u \tau'$ is identically vanishing, due to $SU(2)_L$ gauge invariance, but if we introduce an SU(2) triplet $\phi(1,3)_o$, we can match its fermionic degrees of freedom with those of $H_u$ and $\tau'$, via the terms

$$\lambda_H \int d^4 \theta \frac{X^\dagger H_u^\dagger H_u \tau'}{M^2} + \lambda_{\tau'} \int d^2 \theta \frac{H_u^\dagger H_u \tau'}{m} + \text{c.c.} \ . \quad (12)$$

We take $\phi$ to be neutral under the $R$-symmetry in order to forbid a mass term of the form $\phi^2$ (a small mass will be generated at higher orders since $R$-symmetry is not exact, but will be suppressed by loop factors). This results in the mass terms

$$\mathcal{L} \supset \left( \lambda_H \frac{F}{M^2} \right) H_u^\dagger \phi H_u \overline{\phi} - \left( \frac{\lambda_{\tau'} v^2}{m} \right) \phi \tau' \overline{\phi} - \left( \frac{\lambda_H v}{\sqrt{2} M^2} \right) H_u^\dagger \phi H_u \overline{\phi} + \text{c.c.} \ . \ \quad (13)$$

All fermions thus become massive. Since one of the mass terms above is of order $v^2/m$, the parameter $m$ is required to be at the order of the weak scale in this case.

So far, we have discussed masses for the fermions. The new scalars get soft supersymmetry breaking masses normally, through couplings of the form

$$\frac{X^\dagger X}{M^2} \Phi^\dagger \Phi, \quad (14)$$

where $\Phi$ denotes collectively standard model chiral superfields. This operator induces scalar masses at the order of $m_0 \sim \sqrt{\kappa} (F_X/M)$, which is parametrically larger than the fermion masses by a factor of $(M/v)$, thereby reintroducing the hierarchy problem. However, this problem need not occur if $X$ is part of a strongly coupled sector as in models of conformal sequestering. In such theories, it is possible for $X^\dagger X$ to have a large anomalous dimension in such a way that the dimension of $X^\dagger X$ is $d \simeq 1$. The operator is then suppressed by an additional factor $(\Lambda/v)^{d-2}$, where $\Lambda$ is the scale of strong coupling in this sector. The scalar masses would then be of order $m_0 \sim (\Lambda/v) (\frac{\Lambda}{v})^{d-2}$, which can make the scalar and fermion masses again of the same order. All new fields therefore acquire a mass of order the electroweak scale, rendering the model phenomenologically viable. As in the MSSM, the Higgs mass term gets large negative contributions to its RGE running from top loops, but now it will get even larger contributions from the new heavy fermions. This naturally drives electroweak symmetry breaking in these theories.

The phenomenology of this model is very different from the MSSM. It is in many ways similar to a supersymmetric theory with four generations; experimentally, the quark sector would behave exactly like the usual fourth generation theory. The “lepton” sector is more interesting, since the lepton doublet is missing; it has become the Higgs. However, we have introduced a new field $\phi$ which includes one neutral and two charged degrees of freedom. The spectrum therefore includes one extra “chargino” compared to the MSSM. Furthermore, some fields in the leptonic sector are expected to be quite light, which may lead to interesting signals.

Also, the couplings of the fields in the “lepton” sector are in general quite different, and can potentially be used to distinguish these scenarios. For example, the neutral scalar fields in this sector are the Higgs scalar and $\phi^0$. This is to be compared to the usual fourth generation scenario which has the sneutrino as the neutral field. However, the Higgs scalar couples strongly to the quarks, in particular the top quark and the new fourth generation quarks, while the sneutrino does not have a strong interaction with quarks. This would allow us to distinguish the chiral Higgs scenario from the usual fourth generation scenario, for example by measuring the couplings between the fourth generation quarks and leptons.

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1 Here, we have assumed that the newly added $\phi$ does not develop a vacuum expectation value. This assumption is compatible with radiative electroweak symmetry breaking, since $H_u$ obtains a negative mass squared due to radiative corrections from the large Yukawa couplings discussed above, but $\phi$ does not.

2 Instead of invoking the chiral sequestering mechanism, we may admit a hierarchical mass spectrum between the gaugino and sfermions à la split supersymmetry, which is naturally realized in supergravity mediation without singlet supersymmetry breaking fields. There, the sfermion masses are generated at tree level and are of the order of the gravitino mass, $m_{3/2} = O(100)$ TeV, while the gaugino masses are radiatively generated by anomaly mediation effects. In these cases, we may trade the supersymmetry breaking spurion $X$ for the chiral compensator $\phi = (1 + m_{3/2} \phi^2)$, along with the condition $M \simeq m_{3/2} = O(100)$ TeV.
study of these possibilities would be model dependent, since it is sensitive to the precise spectrum of the theory. We shall leave this for future work.

IV. OTHER MODELS WITH A CHIRAL HIGGS SECTOR

A fourth generation is not the only possibility, and there are other candidates for a chiral Higgs sector. It would be particularly interesting to find models which include no extra colored particles, thereby avoiding the stringent bounds from Tevatron and LHC. Two main challenges which are common to all chiral Higgs models include no extra colored particles, thereby avoiding the stringency of bounds from Tevatron and LHC. Two main challenges which are common to all chiral Higgs models are: avoiding fractionally charged particles (these would be stable and thus severely constrained by cosmology), and giving large enough mass to all new fermions, especially the charged ones. Our requirements from any chiral Higgs sector are that:

- It includes \( H_u(1,2)_{1/2} \), and does not include \( H_d(1,2)_{-1/2} \)
- It is anomaly free
- It does not include any light charged particles (the bounds are roughly around \( \sim 100 \text{ GeV} \), from LEP)
- It does not include new stable charged states, implying no fractionally charged fields in the model. This requirement may be relaxed in scenarios with low scale reheating temperature.

The following are simple examples of models which satisfy all these requirements, including the absence of fractionally charged fields:

1. \( T(1,3)_{-1}, H_u(1,2)_{1/2}, D(1,2)_{7/2}, \rho(1,1), \sigma(1,1)_{-3}, \omega(1,1)_{-4} \): The Lagrangian is given by

\[
\delta L = \int d^2 \theta \left( \frac{\lambda_{ijk}}{m} H_u^i H_u^j \phi \tau^{(i,j)}, z_i H_u^i D \tau^i \right) + \int d^4 \theta \lambda^1 \left( \frac{\lambda_{ijk}}{m} \phi H^i_\tau + y_i^j \phi H^i_\rho + z^j \phi H^i_\rho \right). \tag{17}
\]

2. \( 3 \times \{ H_u^i(1,2)_{1/2}, \tau^{(i,j)}, \rho(1,1)_0, D(1,2)_{-3/2}, \phi(1,3)_0, \sigma(1,1)_0, \omega(1,1)_0 \} \):

This is a chiral three-Higgs doublet model. The Lagrangian is given by

\[
\delta L = \int d^2 \theta \left( \frac{\lambda_{ijk}}{m} H_u^i H_u^j \phi \tau^{(i,j)} + y_i^j H_u^i \phi \tau^j + z_i^j H_u^i \phi \rho \right) + \int d^4 \theta \lambda^1 \left( \frac{\lambda_{ijk}}{m} \phi H^i_\tau + y_i^j \phi H^i_\rho + z^j \phi H^i_\rho \right). \tag{18}
\]

The field contents above are selected examples and by no means constitute an exhaustive list. One general feature, however, seems to be the existence of doubly, and in some cases also triply and quadruply charged particles. Models based on such spectra may lead to novel decays in colliders.

V. DISCUSSION

We have discussed models which are supersymmetric but include only one Higgs doublet. As a first step, we presented a model in which the \( H_d \) superfield is inert and does not contribute to SM fermion masses. This model was analyzed both as an effective field theory, and as a UV complete theory which may include flavorful dark matter with novel phenomenology.

Next, we discussed models with chiral Higgs sectors. These models include only one Higgs doublet, but are nevertheless anomaly free and phenomenologically viable. All the new particles acquire masses at the order of the electroweak scale.

Consider electroweak corrections that affect the \( S \) and \( T \) parameters. Since we have a large number of new particles, these corrections may be large. It would be interesting to see if any of the models above can be compatible with precision electroweak tests.
Furthermore, these models in general should have striking signatures at the LHC. This is because anomaly cancellation requires the existence of several new chiral superfields, which will necessarily have masses at the electroweak scale. Moreover, we find that the new fields are either colored, or have unusual charges, leading to a rich phenomenology at the LHC. Especially, the production cross section of the Higgs boson can be highly enhanced in those models with a mirror fourth generation. For example, a Higgs boson mass in the range of $120 \text{ GeV} < m_h < 600 \text{ GeV}$ has been excluded by CMS at 95% C.L. [13] in models with the fourth generation. Therefore, the idea of a mirror family can be partially tested in near future via the Higgs search (see for example [14, 15] for a recent study).

In all, the detailed investigation of chiral Higgs phenomenology appears to be model dependent, since, as we have shown, there are many possibilities for such models - with qualitatively different field contents. It may however be possible to find generic features of these models, which may allow us to distinguish the chiral Higgs theories from the usual extensions of the MSSM. We hope to return to these questions in future work.

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