SUSY Multi-Step Unification without Doublet-Triplet Splitting

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Abstract. Matter-Higgs unification in string-inspired supersymmetric Grand Unified Theories predicts the existence of colored states in the Higgs multiplets and calls for two extra generations of Higgs-like fields ('unhiggses'). If these states are present near the TeV scale, gauge-coupling unification points to the existence of two distinct scales, $10^{15}$ GeV where right-handed neutrinos and a Pati-Salam symmetry appear, and $10^{18}$ GeV where complete unification is achieved. Baryon-number conservation, while not guaranteed, can naturally emerge from an underlying flavor symmetry. Collider signatures and dark-matter physics may be drastically different from the conventional MSSM.

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1 Introduction

One of the most intriguing ideas for physics beyond the Standard Model are Grand unified theories (GUT), putting together part of or all SM particles in multiplets of one unified gauge group that is broken down to $SU(3)_c \times SU(2)_L \times U(1)_Y$ at the GUT scale. The oldest approaches were based on the groups $SU(5)$ [1] and $SU(4) \times SU(2) \times SU(2)$ [2]. GUT models became much more consistent with the inclusion of low-scale supersymmetry [3] which stabilizes the hierarchies of the GUT and electroweak (EW) scale and allows for an almost exact unification of the gauge couplings. While in the $SU(5)$ GUTs only a partial unification is achieved, in the Pati-Salam (PS) symmetry lepton number is treated as a fourth color. $SO(10)$ [4] includes all matter particles of the SM (including a right-handed neutrino), but it does not unify matter and Higgs representations. This is achieved within the framework of $E_6$ GUTs [5].

All mentioned models share the famous doublet-triplet splitting problem [6]: embedding all states (including Higgs) in complete representations implies the existence of a pair of 'exotic' color-triplet EW-singlet superfields $D$ and $D^c$. Higgs-matter unification furthermore introduces two extra Higgs/$D/D^c$ generations. If these have EW-scale masses, their effect on the running couplings spoils unification. $D/D^c$ superpotential interactions invariant under the GUT symmetries contain both diquark and leptoquark couplings and thus induce rapid proton decay [7]. To avoid this problem, they are usually placed near the GUT scale, although this cannot be explained without further structure beyond the gauge symmetry.

Our goal is to construct a model that avoids the doublet-triplet splitting problem, and solves the $\mu$ problem (i.e. the fact that the SUSY $\mu$ parameter has to be of order the EW scale for successful EW symmetry breaking to happen) of the MSSM simultaneously [8]. Although our model is motivated more from a bottom-up approach, namely reconciling the above-mentioned model-building perspectives with the phenomenological demand to observe hints on the GUT structure directly at LHC, we will describe the model from a top-down view.

2 The model from a top-down perspective

When keeping the triplet partners of the Higgs doublets in the low-energy spectrum, there are two important issues: repairing gauge coupling unification, and much more severe: a mechanism to prevent too rapid proton decay. Solving the first problem relies on the observation that in the MSSM spectrum with triplets the $SU(2)$ and $U(1)$ couplings meet at $10^{14}$ GeV, a natural place for right-handed neutrinos and the seesaw mechanism. Extending the MSSM symmetry group to a left-right symmetry $SU(2)_L \times SU(2)_R$ results in a gauge coupling unification at $10^{21}$ GeV, far above the Planck scale, cf. Fig. 1 dashed lines. But extending $SU(3)_c$ to $SU(4)_c$ (hence, to a PS group) changes the running of $\alpha_s$ and allows for a complete unification directly at the Planck scale (Fig. 1 full lines). Regarding the second problem, the standard way to forbid proton decay in the MSSM, $R$ parity, which forbids both diquark and leptoquark couplings for ordinary quark...
superfields. For the new triplet Higgses these couplings are still allowed (either for the scalars or the fermions), so they must be forbidden by a different mechanism. One way to do is by imposing flavor symmetries (see below).

To implement this together with a complete \( E_6 \) spectrum for the three generations we start with a particle content of a \( N=2 \)-SUSY \( E_8 \) gauge theory. We want to break the \( E_8 \) down to the \( E_6 \times SU(3)_F \) combined gauge and flavor symmetry group. Under \( N=2 \) SUSY there is a \( 248 \oplus \overline{248} \) matter and gauge fundamental representation of \( E_8 \). This decomposes as \( 248 = 27_3 \oplus \overline{27}_3 \oplus 78_i + 1_8 \) under \( E_6 \times SU(3)_F \). That corresponds to a flavor-triplet of matter \( 27_3 \), a mirror matter multiplet \( \overline{27}_3 \), an \( E_6 \) adjoint \( 78_1 \) and the flavor adjoint \( 1_8 \) (cf. e.g. \[9\]).

Somewhat below the Planck scale the breaking of \( N=2 \) SUSY to \( N=1 \) SUSY removes the mirror matter by an infinite (Kaluza-Klein) tower of such multiplets and a quartic coupling which in the \( E_6 \) decomposition contains \( (27_3)^3, (27_3)^4, (27_3)^{ij} \). An asymmetric spurion (condensate) \( (27_3)^{ij} \delta(i,j,\alpha) \), \( \alpha \neq 0 \) breaks \( E_6 \) and removes all mirror matter from the massless spectrum, leaving one zero mode \( (27_3)^0 \). The flavor symmetry group is broken by a colorless spurion, e.g. \( (1_8) \). To reduce the symmetry further down to the PS group, we introduce a spurion \( (\overline{1}_2, \overline{3}_{12,2}) \) which corresponds to a \( \mu \)-term-type coupling of mirror-Higgs superfields which occurs in the decomposition of \( 27_3 \overline{27}_3 \). This also breaks flavor symmetry. An additional allowed spurion would be \( \overline{27}_3 \sim (\overline{\mathbf{1}}_{1,1}) \) which can be used to distinguish the third generation (by itself, the latter would break \( E_6 \) to \( SO(10) \), the standard GUT path).

Similar to the diquark coupling discussed before, the trilinear \( E_6 \) superpotential \( 27_3 \overline{27}_3 \overline{27}_3 \) vanishes identically if flavor symmetry is imposed, so all matter self-interactions are effectively generated by symmetry breaking. Looking at other trilinear terms, we can have \( (27_3 \overline{78}_i \overline{27}_3), (78_1 \overline{78}_i \overline{78}_1), (27_3 \overline{1}_8 \overline{27}_3), \) and \( 1_8 1_8 1_8 \). The effective superpotential results from inserting condensates for \( 27_3 \) and integrating out the remaining fields in \( 78_1 \) and \( 1_8 \). For these, \( E_6 \times SU(3)_F \) invariance allows for mass terms. This construction generates all MSSM superpotential terms, subject to PS symmetry, as well as couplings \( SD^2 D \) and \( SHaHd \). Concerning baryon number, the only dangerous term is \( 78_1 \), \( 78_1 \), \( 78_1 \) which after inserting the (colorless) condensates into \( 27_3 \overline{78}_i \overline{27}_3 \) and integrating out the \( 78_1 \) results in additional trilinear matter couplings. However, the color-triplet leptoquarks \( X \) contained in the \( 78_1 \) do not have a self-coupling: \( XXX \) again vanishes by total antisymmetry with respect to all color, left, and right indices.

At \( 10^{14} - 10^{15} \) GeV, a field with right-handed neutrino quantum numbers present among the color- and flavorless fields contained in the \( 78_1 \sim W_R^{23} \) condenses. A quartic term \( (27_3 \overline{78}_i \overline{27}_3)^2 \) in the effective superpotential generates a right-handed neutrino mass from the diagram in Fig. 2. This is in accordance with the seesaw mechanism and breaks the PS symmetry down to the SM gauge group. Near the electroweak scale, an \( S \) condensate generates a \( \mu \) term (like in the NMSSM), and standard radiative breaking of the electroweak symmetry can occur as in the MSSM.

At this point we reconcile possible operators mediating proton decay and how they are forbidden in the model mentioned above. Considering the exchange of gauge superfields, the proton-decay scale is lifted together with the GUT scale to \( 10^{15} \) GeV since PS gauge bosons do not mediate proton decay. The PS-invariant superpotential terms containing \( D \) and \( D^c \) are \( \overline{3}_{12} 6_{1,2} \overline{3}_{1,2} \) and \( 4_{2,1} 6_{1,4} 4_{2,1} \). The first term induces a leptoquark coupling \( u^cD \), together with a diquark coupling \( u^cD^c \), the second term provides leptoquark couplings \( D^c\ell q \) and diquark couplings \( Dqq \). Unfortunately, at least one of them is required to make the \( D \) particles decay, so not all of them can be forbid-
3 Phenomenology

The low-energy spectrum of the abovementioned model is quite similar to the standard \( E_6 \) models, containing one to three families of pairs of Higgses (including their fermionic partners) and the corresponding leptoquarks at the TeV scale. Furthermore, there are up to three generations of singlet scalars and their fermionic partners. In case of the complete content, there are 6 scalar leptoquarks \( D_L \) and \( D_R \) and the 3 leptoquarkinos, \( \bar{D} \). In addition to the MSSM Higgses, 4 charged and 14 neutral (un-)Higgses (for an overview of non-standard Higgses, see [10]), 2 additional charginos and 7 additional neutralinos.

Concerning the additional singlets, there are two different possibilities: either there is a gauged \( U(1) \) symmetry with a corresponding \( Z' \) gauge boson at the TeV scale which protects the singlets and also the leptoquarks directly from getting GUT scale masses. Or this gauged symmetry is broken at the GUT scale but remains valid as a global symmetry down to the TeV scale. Explicit symmetry-breaking operators are induced that avoid massless axions. At the scale of soft SUSY breaking, VEVs are allowed for the neutral components of \( H_u, H_d \), and for \( S \). In all non-minimal versions of the model, these condensates, \( \langle H_u \rangle, \langle H_d \rangle, \langle S \rangle \), are vectors in family space. The Higgs and \( S \) superfield vectors can be rotated such that only one component, the third one, gets a VEV and provides MSSM-like \( H_u \) and \( H_d \) scalars and higgsinos.

Yukawa couplings to matter are possible also for the two unhiggs generations \( h_u, h_d, \sigma \) that do not get a VEV [11]. To avoid FCNCs via double exchange of charged unhiggses, the Yukawa matrix entries for them should either be small or vanish exactly [12]. The latter case is equivalent to an extra \( Z_2 \) symmetry, \( H \)-parity, which is odd just for the unhiggs superfields. Conservation of \( H \)-parity would make the lightest unhiggs (or unhiggsino) a dark-matter candidate [13], adding to the lightest superparticle (LSP) as the dark-matter candidate of \( R \)-parity conservation. Since proton decay is already forbidden by flavor symmetries, we could alternatively drop lepton number and thus introduce the full phenomenology of \( R \)-parity violation, while dark matter is provided by unhiggses.

Even if the unhiggs \( h_u, h_d \) have negligible couplings to ordinary matter, they can still be pair-produced at colliders. Their decays involve ordinary Higgses (including singlets), gauge bosons, or charginos and neutralinos. Some of these signals are detectable at the LHC, all are easily identifiable at the ILC. Unhiggses could also occur in decay cascades of higher-level Higgses, charginos, and neutralinos if kinematically allowed. Alternatively, if \( H \)-parity does not play a role, unhiggs may couple significantly to some light quarks and leptons. In this case, there is resonant production in \( q \bar{q} \) annihilation.

The particles associated with singlet superfields \( S \) consist of one scalar, one pseudoscalar, and one neutralino each. They are all neutral and mix with other Higgs and higgsino states. Production and decay occurs via mixing only, signals are thus similar to MSSM Higgses and neutralinos.

The leptoquark superfields \( D \) and \( D^c \) acquire Dirac masses proportional to \( \langle S \rangle \). The masses are considerably enhanced by renormalization-group running, but some of them could be suppressed by small Yukawa couplings to \( S \). Thus, at the LHC we expect up to three down-type scalar leptoquarks with arbitrary masses. Depending on the structure of leptoquark couplings, various decay patterns are possible. The most likely variant is dominant coupling to the third generation, so leptoquarks are pair-produced in \( gg \) fusion and decay into \( t\tau \) or \( b\nu_\tau \) final states. They would also show up in cascades of gluino or squark decay, if kinematically allowed. The superpartners (leptoquarkinos) should be somewhat lighter, decaying into \( t\tau, t\tau, b\nu_\tau \), or \( b\nu_\tau \).

The role of flavor symmetry in prohibiting diquark couplings of \( D \) fields suggests another scenario: if the dominant terms that induce leptoquark couplings exhibit flavor symmetry, leptoquark decays involve all generations simultaneously. This would lead to distinctive signatures such as \( t\mu, t\tau \), or light jet plus \( \mu \) or \( \tau \). Additional production channels \( g g \rightarrow D t \) would appear. Analogous statements hold for the corresponding fermion superpartners \( D \).

The next step is the calculation of the low-energy spectrum from certain high-scale boundary conditions [14]. In [14] we developed a program for solving numer-
ically the system of renormalization group equations (RGEs) of the SUSY and soft breaking parameters, where special care has to be taken to include the flavor structure of the equations. E.g. the RGE for the Yukawa coupling $Y_{ijk}$ for $H_u^u H_d^u \to i d Y_{ijk} / d \log \mu = \frac{1}{16\pi^2} \left( \begin{array}{l} 3 Y_{ijm} Y_{rjs} + Y_{rjs}^v Y_{rmk}^v \end{array} \right) Y_{imn}^{\nu} + Y_{rjs}^v \left( \begin{array}{l} 3 Y_{rsm} Y_{ijm} + Y_{rsm}^v Y_{rsm}^v \end{array} \right) Y_{rsk}^{\nu} + Y_{rsm}^v \left( \begin{array}{l} 3 Y_{irs} S_{rsm} Y_{imk} \end{array} \right) Y_{rsk}^{\nu} - \left( \frac{3}{2} g_1^2 + 3 g_2^2 + \frac{1}{2} (Q_S^2 + Q_d^2 + Q_u^2) g_3^2 \right) Y_{ijk}\right)}$

Here, $Y_u$ and $Y_d$ are the standard MSSM Yukawa couplings for up- and down-quark superfields, while $Y_{SD}$ is the coupling for $S_i D_j D_k$ and the fields $Q_i$, $Q_d$, and $Q_S$ are the $U(1)'$ charges of the Higgs doublets and singlets, respectively, while $g_3$ is the corresponding gauge coupling. To study the collider phenomenology of this model, the model is being implemented (following the conventions of [15]) into the event generator WHIZARD [16,17,18], which is well-suited for models beyond the SM [19,20,21].

4 Conclusions

In conclusion, we have explored a SUSY-GUT scenario without doublet-triplet splitting, such that the low-energy spectrum contains color-triplet leptoquarks $D$ and their superpartners. The constraint of gauge-coupling unification then points to the existence of two distinct high-energy scales. The first threshold is at $10^{15}$ GeV where the MSSM gauge group is extended to the PS group $SU(4)_C \times SU(2)_L \times SU(2)_R$ and right-handed neutrino masses are generated. At the higher energy $10^{18}$ GeV, slightly below the Planck scale, complete unification (e.g., $E_6$) is located, possibly in the context of a superstring theory.

While gauge interactions in a PS GUT do not trigger proton decay, proton decay via the superpotential can be eliminated by an underlying flavor symmetry. $R$-parity conservation is no longer mandatory. While the LHC will serve as an ideal machine to discover especially the colored part of the spectrum of this model, an ILC is probably needed to disentangle the complex structure of the weakly-interacting part of that model.

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