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Unification Without Doublet-Triplet Splitting

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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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Grand unified theories (GUT) of all particle-physics interactions have drawn great attention since the classic path of $SU(5)$ unification has been discovered [1]. In the supersymmetric version (MSSM) [2, 3], the running effective couplings of the Standard-Model (SM) gauge group meet almost exactly at the GUT scale $M_{\rm GUT} \approx 10^{16}$ GeV. The $SO(10)$ extension [4] furthermore incorporates right-handed neutrinos, while trinification ($SU(3)^3 \otimes Z_3$) [5, 6, 7] and E_6 GUTs [8] unify Higgs and matter representations.

All mentioned models share the famous doublet-triplet splitting problem [9]: embedding all states (including Higgs) in complete representations implies the existence of a pair of 'exotic' color-triplet electroweak-singlet superfields D and D^c. Higgs-matter unification furthermore introduces two extra Higgs/D/D^c generations. If these have electroweak-scale masses, their effect on the running couplings spoils unification. GUT-invariant D/D^c superpotential interactions contain both diquark and leptoquark couplings and thus induce rapid proton decay [10]. To avoid this problem, they are usually placed near the GUT scale, although this cannot be explained without further structure beyond the gauge symmetry.

Relaxing GUT constraints on the superpotential, e.g., in 'string-inspired' E_6 models [11], the proton-decay problem can be removed by imposing discrete symmetries that eliminate either diquark or leptoquark couplings [12]. However, the lack of coupling unification seems to disfavor D/D^c in the light spectrum; recent phenomenologal studies [13] rely on extra states from incomplete representations to make conventional unification work.

Nevertheless, it is worthwhile to inspect the renormalization-group flow of a pure spectrum of complete GUT representations. In particular, we consider the fundamental **27** of E_6 that includes, for each matter generation, all quark and lepton fields, Higgs, D/D^c, and a colorless singlet S.

In such a model, the three running gauge couplings do not intersect at a single point. Still, the $SU(2)_L$ and $U(1)_Y$ couplings do meet at 10^{15} GeV (Fig. 1). This is a realistic mass scale for right-handed neutrinos ν^c, in accordance with see-saw numerics if we take into account a possible hierarchy in right-handed neutrino masses. Adding the ν^c fields at that scale, the SM gauge group may be extended to a left-right symmetric model. The combined left-right weak coupling runs differently from the QCD coupling and unifies with it at 10^{21} GeV. This is, however, above the Planck scale and thus does not lead to a viable GUT model.

Instead, we can achieve unification below the Planck scale by slightly extending this model. At 10^{15} GeV, we postulate the appearance of the Pati-Salam (PS) gauge symmetry $SU(4)_C \times SU(2)_L \times SU(2)_R \times Z_2$ [14]. The corresponding renormalization-group flow is shown in Fig. 1 (full lines). The ultimate unification scale where a symmetry such as $SO(10)$ or E_6 could emerge is about 10^{18} GeV, perfectly consistent with string theory [15]. (For alternative multi-step unification scenarios with and without exotic matter cf. [16].)

Breaking the PS gauge group down to the MSSM gauge group at 10^{15} GeV is achieved by just integrating out the right-handed neutrinos, so there is no need for a breaking mechanism beyond the one that generates ν^c Majorana masses. Furthermore, PS gauge bosons do not mediate proton decay. Considering gauge-superfield exchange only, the proton-decay scale is thus lifted to 10^{18} GeV.

Regarding proton decay via superpotential interactions, the PS symmetry does not put Higgs fields and D/D^c in a common multiplet; they fill independent $\mathbf{1}_{2,2}$ and $\mathbf{6}_{1,1}$ representations, respectively. However, coupling unification in this model requires their coexistence in the light spectrum. Coupling the latter to matter fields in a PS-invariant way simultaneously induces leptoquark and diquark couplings and thus rapid proton decay. Such a term is unfortunately required to make the D particles

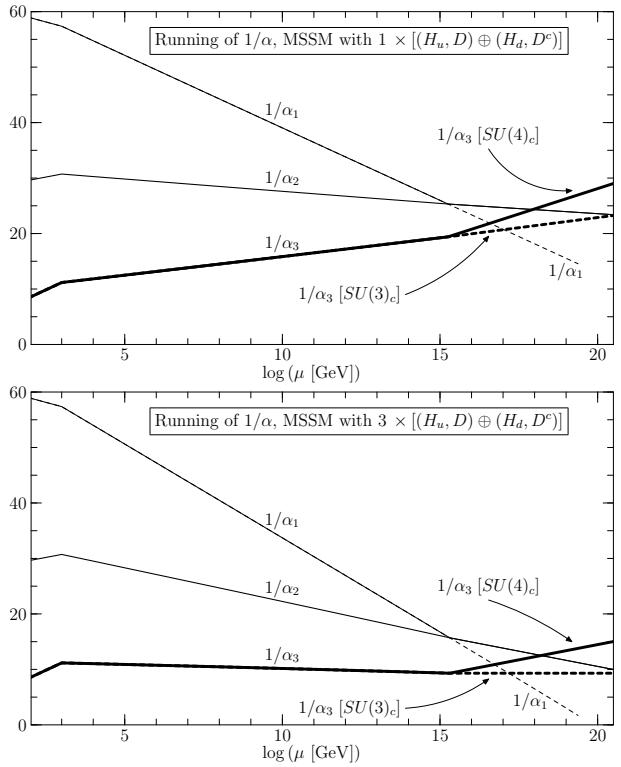

FIG. 1: One-loop running couplings for the MSSM spectrum with one (top) or three (bottom) complete matter/Higgs families and left-right symmetry above the neutrino mass scale. Dashed: $SU(3)_C \times SU(2)_L \times SU(2)_R$ (SM with left-right symmetry). Full: $SU(4)_C \times SU(2)_L \times SU(2)_R$ (Pati-Salam). The $SU(2)_L$ is the same in both cases.

decay.

To eliminate the dangerous terms we can make use of the fact that there are three generations of matter. In the absence of a superpotential, a model with three matter/Higgs families has a $SU(3)_F$ flavor symmetry. (The non-anomalous $SO(3)_F$ subgroup suffices.) Imposing flavor symmetry on the diquark couplings on top of $SU(2)_L$ and $SU(2)_R$ symmetry uniquely selects the structure

$$D q_L q_L = \epsilon^{abc} \epsilon_{\alpha\beta\gamma} \epsilon_{jk} D^a_\alpha (q_L)^b_{\beta j} (q_L)^c_{\gamma k}$$

(D^c analogous), where (a, b, c), (α, β, γ), and (i, j, k) are indices in flavor, color, and $SU(2)_L$ space, respectively. Due to the total antisymmetry of three ϵ symbols, this term exactly vanishes. This property continues to hold if we impose larger gauge symmetries (PS, $SO(10)$, E_6) on the superpotential, as long as $SU(2)_L \times SU(2)_R$ is a subgroup. Flavor symmetry in conjunction with color and left-right symmetry thus eliminates diquark couplings, and baryon number automatically emerges as a symmetry of the superpotential.

While $SU(2)_L$ is exact down to the TeV scale, breaking $SU(2)_R$ and $SO(3)_F$ at high energies might re-introduce D/D^c diquark couplings and thus proton-decay operators. To exclude them, we have to impose baryon number on all $SU(2)_R$- and $SO(3)_F$-breaking spurions that connect D or D^c with other fields: they have to involve quark fields in color-singlet pairs (or respect flavor symmetry). This is easy to realize since any spontaneous symmetry-breaking can be associated to condensates at most bilinear in fields of the fundamental representation. After integrating out gauge superfields, baryon number emerges as an exact symmetry of the low-energy theory. The flavor symmetry needs not leave obvious traces.

We illustrate this in form of a toy model that does not refer to specific features of supergravity or string theory. Let us assume that all matter and associated fields derive from fundamental **248** representations of E_8 [17], which has $E_6 \times SU(3)$ as a maximal subgroup. We identify E_6 with the GUT symmetry and $SU(3)$, departing from the standard construction for string compactification [11], with flavor. The multiplet decomposes into a flavor-triplet of matter $\mathbf{27}_3$, a mirror image triplet $\overline{\mathbf{27}}_{\bar{3}}$, an E_6 adjoint $\mathbf{78}_1$, and the $SU(3)_F$ adjoint $\mathbf{1}_8$ (cf. e.g. [18]).

We may assume an infinite (Kaluza-Klein) tower of such multiplets and introduce quartic couplings which in the E_6 decomposition contain $(\mathbf{27}_3)_i (\overline{\mathbf{27}}_{\bar{3}})_i (\mathbf{27}_3)_j (\overline{\mathbf{27}}_{\bar{3}})_j$. An asymmetric spurion (condensate) $\langle (\mathbf{27}_3)^a_i (\overline{\mathbf{27}}_{\bar{3}})^b_j \rangle = \delta^{ab} \delta_{j,i+1}$ breaks E_8 and removes all mirror matter from the massless spectrum, leaving one zero mode $(\mathbf{27}_3)_0$. To reduce the symmetry further down to the Pati-Salam group, we introduce a spurion $\langle \overline{\mathbf{1}}_{2,2} \overline{\mathbf{1}}_{2,2} \rangle$, i.e., the μ-term-type coupling of mirror-Higgs superfields which occurs in the decomposition of $\overline{\mathbf{27}}_{\bar{3}} \overline{\mathbf{27}}_{\bar{3}}$. This also breaks flavor symmetry. To distinguish the third generation, we can also allow for $\langle \overline{\mathbf{27}}_{\bar{3}} \rangle \sim \langle \overline{\mathbf{1}}_{1,1} \rangle$. (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 $\mathbf{27}_3\, \mathbf{27}_3\, \mathbf{27}_3$ 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 $(\mathbf{27}_3\, \mathbf{78}_1\, \overline{\mathbf{27}}_{\bar{3}})$, $(\mathbf{78}_1\, \mathbf{78}_1\, \mathbf{78}_1)$, $(\mathbf{27}_3\, \mathbf{1}_8\, \overline{\mathbf{27}}_{\bar{3}})$, and $\mathbf{1}_8\, \mathbf{1}_8\, \mathbf{1}_8$. The effective superpotential results from inserting condensates for $\overline{\mathbf{27}}_{\bar{3}}$ and integrating out the remaining fields in $\mathbf{78}_1$ and $\mathbf{1}_8$. For these, $E_6 \times SU(3)_F$ invariance allows for mass terms.

This construction generates all MSSM superpotential terms, subject to Pati-Salam symmetry, and couplings SD^cD and SH_uH_d. Concerning baryon number, the only dangerous term is $\mathbf{78}_1\, \mathbf{78}_1\, \mathbf{78}_1$ which after inserting the (colorless) condensates into $\mathbf{27}_3\, \mathbf{78}_1\, \overline{\mathbf{27}}_{\bar{3}}$ and integrating out the $\mathbf{78}_1$ results in additional trilinear matter couplings. However, the color-triplet leptoquarks X contained in the $\mathbf{78}_1$ do not have a self-coupling: XXX again vanishes by total antisymmetry with respect to all color, left, and right indices.

A field with right-handed neutrino quantum numbers is present among the color- and flavorless fields contained in the $\mathbf{78}_1$. If this condenses, a quartic term $(\mathbf{27}\, \mathbf{78}\, \overline{\mathbf{27}})^2$ in the effective superpotential generates a right-handed

neutrino mass in accordance with the seesaw mechanism [19] and breaks the PS symmetry down to the SM gauge group. Near the electroweak scale, an S condensate generates a μ term, and standard radiative breaking of the electroweak symmetry can occur.

We do not attempt to extend this model to a full theory of gauge and flavor structure. Further studies should answer the question whether some construction that implements the main ideas can account for realistic mixing patterns in both quark and lepton sectors.

Departing from particular toy-model features, the low-energy particle spectrum of the Pati-Salam GUT models discussed here is a subset of the well-known spectrum of E_6-type models, without the need for Higgs states outside the E_6 matter multiplets [20]. It depends on the number of non-MSSM (Higgs, leptoquark) generations that survive at low energies. The minimal version contains just the MSSM spectrum, augmented by one color-triplet of D leptoquark superfields. The maximal version displays three full families of E_6 matter including three D leptoquarks, three families of superfields with the quantum numbers of the MSSM Higgs doublets, and three SM singlet superfields S.

A natural mechanism to keep the complete spectrum light is to have a $U(1)$ subgroup of the E_6 gauge symmetry unbroken. Soft supersymmetry (SUSY) breaking would trigger radiative breaking of this extra $U(1)$ at the TeV scale. All Higgs and leptoquark fields have $U(1)$ charges such that GUT-scale mass terms are excluded, implying the existence of a Z' boson in the TeV range [21]. Alternatively, this local symmetry may be broken at the high scale. In that case, vacuum expectation values (VEVs) for S fields could provide GUT-scale mass terms for some Higgs/leptoquark families. To avoid axions, GUT-scale $U(1)$ breaking should, via higher-dimensional terms, induce explicit $U(1)$-breaking in the low-energy Lagrangian. These terms could be in the superpotential (S^3) or in the soft SUSY-breaking part.

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, σ that do not get a VEV [22]. To avoid FCNCs via double exchange of charged unhiggses, the Yukawa matrix entries for them should either be small [13] 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 [23], adding to the lightest superparticle (LSP) as the dark-matter candidate of R-parity conservation.

Incidentally, baryon-number conservation via flavor symmetry eliminates the need for R-parity conservation. If we keep lepton number as an accidental symmetry below PS-breaking, R-parity conservation emerges as a derived result. Alternatively, we could drop lepton number and thus introduce the full phenomenology of R-parity violation, while dark matter is provided by unhiggses.

Even if the unhigges 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, unhigges 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 $\tilde{t}\tau$, $t\tilde{\tau}$, $\tilde{b}\nu_\tau$, or $b\tilde{\nu}_\tau$.

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 $t\mu$, te, or light jet plus μ or τ. Additional production channels $gq \to D\ell$ would appear. Analogous statements hold for the corresponding fermion superpartners $\tilde{D}$.

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 Pati-Salam 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 Pati-Salam GUT do not trigger proton decay, proton decay via superpotential terms can be eliminated by an underlying flavor symmetry. R-parity conservation is no longer a requirement. Combining this with another symmetry that forbids FCNCs, sources for dark matter different from the MSSM appear. Since the model has a considerable quantity of new parameters in the superpotential, there are no unique predictions for their masses or non-gauge interactions. The LHC will certainly allow for discovery or exclusion of leptoquark/-inos up into the TeV range. The (optional) presence of a Z' could easily be established. On the other hand, some weakly interacting states are easy to miss at the LHC, and a thorough analysis at the ILC will likely be needed for completely uncovering this sector.

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