RAPID COMMUNICATIONS

PHYSICAL REVIEW D VOLUME 45, NUMBER 11 1 JUNE 1992

Desert grand unified theories and new light degrees of freedom

Thomas G. Rizzo
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
and Ames Laboratory and Department of Physics, Iowa State University, Ames, Iowa 50011
(Received 30 October 1991)

We show that by introducing additional degrees of freedom with masses of the order of the electroweak scale the usual predictions for the proton lifetime and $\sin^2\theta_W$ obtained in the contexts of grand-unified-theory models with deserts can now be made to agree with current experimental data. We tabulate a number of possible quantum number assignments for these new particles.

PACS number(s): 12.10.Dm, 14.80.−j

In a recent paper, Amaldi, deBoer, and Fürstenau [1] showed that the minimal supersymmetric (SUSY) extension of the standard model (SM), embedded in SUSY SU(5), leads to values of the coupling constants which are in agreement with current high-precision data [2] from the CERN e^+e^- collider LEP and is consistent with existing proton lifetime [3] limits. By way of contrast, the SM without SUSY [embedded in ordinary SU(5)] leads to a value of $x_w = \sin^2\theta_W(M_Z)$ which is too small by many standard deviations and a proton lifetime which violates present experimental bounds. In fact, these results are quite general in that they hold for any grand unified theory (GUT) breaking directly to $SU(3)_C \times SU(2)_L \times U(1)_Y$ at a scale M_u provided that (i) threshold effects near M_u are small and (ii) the trace of the three generators satisfies the usual condition $\mathrm{Tr}T_C^2 = \mathrm{Tr}T_L^2 = \frac{3}{5}\,\mathrm{Tr}(Y/2)^2$.

Assuming (i) and (ii) are true for an arbitrary GUT breaking directly to the SM (without SUSY) we would like to know whether the introduction of additional degrees of freedom near the electroweak scale could also resolve the difficulties of non-SUSY SU(5); i.e., we want to examine if such an augmented version of the SM can lead to values of x_W and M_u which are in agreement with current data. We will make no reference to the specific nature of the GUT model and demand only that (i) and (ii) be satisfied.

Some initial work along these lines for non-SUSY SU(5) has been performed by Murayama and Yanagida (MY) [4]. These authors consider the use of a pair of light leptoquark scalars, together with a pair of conventional Higgs doublets, introduced with masses of the order of the weak scale. Using the values of $\alpha(M_Z)$ and $\sin^2\theta_W(M_Z)$ as input, they calculate the value of M_u and the unification coupling α_u by using the renormalization-group equations (RGE's) for α_L and α_Y (since they are more precisely known) and, subsequently, the α_s RGE is used to calculate $\alpha_s(M_Z)$. They find that M_u is sufficiently large to account for the required longer proton lifetime and that the predicted value of $\alpha_s(M_Z)$ is in excellent agreement with data from LEP [2].

Is this the only set of fields that can do the job? In principle there are many other solutions that may work as well or even better than the MY scheme. The goal here is to test the uniqueness of the MY solution and get a feel for just how easy it is to "repair" the standard desert GUT scenario.

What kinds of particles can we add to the SM? There are a huge number of possibilities; we will assume that the new particles transform as either **1**, **3**, **6**, or **8** under $SU(3)_C$, are either singlets, doublets, or triplets under $SU(2)_L$, and take the electric charge of isomultiplet members with the highest weight to be $Q=0$, ± 1, 2/3, $-1/3$, 5/3, or 2 which gives us 84 possible quantum number assignments. If these particles are fermions, we cancel anomalies by demanding that they are vectorlike; i.e., they come in pairs. In principle, these new degrees of freedom can occur together so that the following combinations are considered: (a) one or two pairs of vectorlike fermions, (b) a single complex scalar, (c) two complex scalars with possibly different quantum numbers, (d) one or two vectorlike fermion pairs plus a complex scalar with possibly different quantum numbers, and (e) same as (d) but with two identical scalars. (We will assume that all new degrees of freedom we introduce are degenerate.) Although this list is not exhaustive it leaves us $\approx 4.3\times 10^4$ cases to examine. Thus, to reduce the number of possibilities further, we demand that in addition to (i) and (ii) we also require that (iii) $SU(3)_3$ remain asymptotically free and (iv) M_u not exceed the Planck scale $M_{\rm Pl}$. Both of these constraints are relatively weak. As further "first-pass" constraints we will demand that (v) $M_u \geq 2.5 M_u^{\rm SM}$ to satisfy proton lifetime requirements and (vi) $0.10 \leq \alpha_s(M_Z) \leq 0.13$, both of which can be tightened up subsequently. We will assume $M_u^{\rm SM} = 2\times 10^{14}$ GeV in our analysis when comparing with the usual SU(5) prediction.

For purposes of comparison, our analysis follows that of MY; we take the values of $\alpha_Y^{-1}(M_Z) = 58.83$ and $\alpha_L^{-1}(M_Z) = 29.85$ from LEP data and calculate M_u, α_u, and $\alpha_s(M_Z)$. This procedure thus incorporates the correct value of x_W from the beginning. In performing the calculation we assume (i) and (ii) are valid and demand that (iii) and (iv) also hold. Of the 4.3×10^4 cases considered above only 67 clearly satisfy the constraints with 6 more being (at best) marginal in that M_u was found to be very close to $M_{\rm Pl}$. Narrowing the range of $\alpha_s(M_Z)$ to the interval 0.105–0.120 favored by LEP reduces the number of distinct allowed cases to only 24. *No* case passes when only a single additional field (or pair of fields) is added to the conventional SM particle spec-

TABLE I. Quantum number assignments for various scenarios that satisfy the constraints discussed in the text. S (F) indicates that the quantum numbers following it refer to a complex scalar (vectorlike fermion) representation. d_C (d_I) is the dimensionality of the representation under $SU(3)_C$ ($SU(2)_L$) and Q is the electric charge of the isomultiplet member of highest weight. N_A (N_B) is the number of fields of type A (B) in the scenario.

Scenario		N_A	d_C^A	d_I^A	Q^A		N_B	d_C^B	d_I^B	Q^B
1	S	1	8	1	2/3	S	1	3	3	2
2	S	2	3	2	2/3	S	2	1	2	0,1
3	S	2	6	2	0,1	S	2	1	3	5/3
4	S	2	6	2	2/3	S	2	1	3	1
5	F	1	3	2	2/3	F	1	1	1	± 1
6	F	1	3	2	0,1	S	1	8	2	2/3
7	F	1	3	2	2/3	S	1	1	1	± 2
8	F	1	3	2	2/3	S	2	3	1	± 1
9	F	1	3	1	0	S	2	1	3	5/3
10	F	1	3	1	$-1/3$	S	2	1	3	2
11	S	1	8	1	2/3	S	1	3	1	5/3
12	S	1	8	2	2/3	S	1	1	3	2
13	F	1	3	2	2/3	F	1	3	1	0
14	F	1	1	2	2/3	F	1	8	2	2/3
15	F	1	3	2	2/3	S	2	3	1	2/3
16	F	2	1	2	0,1	S	1	8	2	0,1
17	F	2	1	2	2/3	S	1	6	1	0
18	F	2	1	2	2/3	S	1	6	1	$-1/3$
19	F	2	1	1	0	S	1	3	3	5/3
20	F	2	3	1	2/3	S	1	6	3	2
21	F	2	3	2	0,1	S	1	8	1	0
22	F	2	3	2	0,1	S	1	8	1	$-1/3$
23	F	2	1	2	2/3	S	2	6	2	0,1
24	F	2	2	2	2/3	S	2	8	2	$-1/3$

TABLE II. Values of M_u/M_u^{SM}, $\alpha_s(M_Z)$, and α_u^{-1} predicted by the 24 scenarios listed in Table I which satisfied the constraints discussed in the text.

Scenario	M_u/M_u^{SM}	$\alpha_s(M_Z)$	α_u^{-1}
1	8.5	0.113	35.5
2	2.8	0.113	38.4
3	5.2×10^2	0.114	28.9
4	5.2×10^2	0.114	28.9
5	2.8	0.113	35.3
6	6.9×10^2	0.117	28.9
7	2.8	0.113	35.3
8	7.6	0.112	35.5
9	5.4	0.120	38.6
10	2.8	0.113	38.4
11	3.2	0.105	35.3
12	2.9×10^2	0.110	36.2
13	2.2×10^2	0.108	36.1
14	2.2×10^2	0.108	36.1
15	10.6	0.105	35.5
16	2.8	0.113	32.2
17	6.8	0.111	38.7
18	3.5	0.106	38.5
19	1.5×10^2	0.116	36.0
20	2.2×10^2	0.119	25.4
21	45.0	0.117	25.6
22	17.0	0.109	25.7
23	6.9×10^2	0.117	28.9
24	3.9×10^2	0.112	10.8

trum.

Table I lists the quantum numbers for these 24 surviving cases while Table II shows their corresponding prediction for M_u/M_u^{SM}, $\alpha_s(M_Z)$, and α_u^{-1}. As can be seen from these results, several scenarios lead to values of $M_u/M_u^{SM} > 100$ implying that proton decay will remain unobservable unless it process through some mechanism in these cases other than super-heavy-gauge-boson exchange [as it does in SUSY SU(5)]. Note that if one restricts the quantum numbers to be more "conventional," i.e., isosinglets and isodoublets which are color singlets and triplets with typical SM electric charges then $2.8 \leq M_u/M_u^{SM} < 200$ for the survivors. All of the scenarios predict a rich phenomenology near the scales currently being probed by colliders.

In almost all cases that pass our constraints, color exotic fermions or scalars are required to exist with masses ≈ 100 GeV or so. Such particles should be quite copiously produced at hadron colliders and possess pair-production cross sections at least several times larger than ordinary quarks [5]. If they decay primarily into multijet final states we can only probe for them up to masses of order 80 GeV at the Fermilab Tevatron unless extremely high integrated luminosities (L) can be obtained [5]. For such small masses LEP already supplies strong constraints [2] on their existence. The situation for the CERN Large Hadron Collider (LHC) and Superconducting Super Collider (SSC) is more optimistic with masses as large as the 0.5–1.7 TeV range possibly producing observable signal rates above background depending upon L, $\sqrt{s}$, and whether fermions or scalars are being considered. In the case where these exotics have leptoquark-type quantum numbers, they may be observable at the DESY ep collider HERA [6], as discussed by MY, provided their masses are $\lesssim 250$ GeV. The worst-case scenario occurs for exotics which are color singlets since they are most easily produced at e^+e^- colliders. Thus to probe the mass region for such particles beyond $\simeq 90$ GeV accessible at LEP II one would need to make use of a higher-energy e^+e^- machine such as the Next Linear Collider (NLC) [7] which would provide very clean production signatures.

The purpose of this analysis was not to be exhaustive, but to give a feeling as to how easy (or difficult) it is to "save" the conventional "desert approach" to GUT's given the recent improvements in coupling-constant determinations at LEP. We have found that only a tiny fraction ($\lesssim 0.7\%$) of the possibilities here examined satisfy our constraints but all of them can lead to exciting signatures for new physics of existing and planned colliders.

The author would like to thank J. Hewett and W. Buchmüller for discussion related to this work. This research has been supported by the U.S. Department of Energy, Division of High Energy Physics, Contracts No. W-31-109-ENG-38 and No. W-7405-Eng-82.

[1] V. Amaldi, W. deBoer, and H. Fürstenau, Phys. Lett. B **260**, 447 (1991).

[2] J. Carter, in Proceedings of the Joint International Lepton-Photon Symposium and Europhysics Conference on High Energy Physics, Geneva, Switzerland, 1991, edited by S. Hegarty, K. Potter, and E. Quercigh (unpublished).

[3] K. S. Hirata *et al.*, Phys. Lett. B **220**, 308 (1989); S. Seudel *et al.*, Phys. Rev. Lett. **61**, 2522 (1988).

[4] H. Murayama and T. Yanagida, Tohuku University Report No. TU-370, 1991 (unpublished).

[5] For a recent discussion of the production of color exotics at hadron colliders, see R. S. Chivukula *et al.*, Phys. Lett. B **257**, 403 (1991); and Harvard University Report No. HUTP-91, 1991 (unpublished).

[6] W. Buchmüller *et al.*, Phys. Lett. B **191**, 442 (1987).

[7] For a discussion of exotic fermion production at the NLC, see W. Buchmüller, at Workshop on Physics With Linear Colliders, Saariselka, Finland, 1991 (unpublished).