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Terascale remnants of unification and supersymmetry at the Planck scale

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We predict new particles at the terascale based on the assumptions that the standard model gauge interactions are unified around the gravitational scale with a big desert and new particles originate from hypermultiplets as remnants of supersymmetry, and propose a theoretical framework, which has predictability, at the terascale and beyond.

Subject Index B40, B42

1. Introduction

Various experimental results have provided useful hints to exploring the physics beyond the standard model (SM).

The first hint is the precision measurements of gauge coupling constants at LEP [1]. These values suggest that the gauge interactions can be unified at a high-energy scale M_{U}, with the advent of new particles [2–5].

The second is the discovery of the Higgs boson at LHC [6,7]. From the observed value of mass $m_h \doteqdot 126\,\text{GeV}$, the quartic self-coupling constant of the Higgs boson is estimated as $\lambda \doteqdot 0.131$, using the mass formula $m_h = \sqrt{2\lambda}v$ and the vacuum expectation value (VEV) of the Higgs boson $v = 246\,\text{GeV}$.

The third is that superpartners have not yet been discovered. The gauge hierarchy problem is revisited, in the case that the physics beyond the terascale is relevant to the SM [8,9]. If we require that m_h should be determined without fine tuning, we have an option that there is a big desert from the terascale to M_{U}, and the initial value of m_h is fixed by the physics at M_{U} (protected against large radiative corrections by some mechanism or symmetry) [10]. Hence new charged particles must appear around the terascale if it exists until M_{U}.

The last is that a definite discrepancy has not yet been observed between the predictions in the SM (modified with massive neutrinos) and experimental results. This suggests that, in cases with new particles, their effects must be canceled or suppressed for some reason. A clue might be supersymmetry (SUSY), which can induce a cancellation between contributions from bosons and those from fermions and control interactions among particles [11]. There is a possibility that new massive particles originate from hypermultiplets and the power of SUSY partially and indirectly remains, although SUSY is broken down around M_{U}.

Therefore, it is interesting to pursue the physics at the tera- and unification scales based on the above hints. In this letter, we specify new particles at the terascale based on the assumptions that the

SM gauge interactions are unified around the gravitational scale with a big desert and new particles come from hypermultiplets. We propose a theory, which has the power to determine some coupling constants, at the terascale and beyond.

The outline of this letter is as follows. In the next section, we explore new particles at the terascale, as remnants of gauge unification and SUSY. We construct a theory including new particles in Sect. 3. In the last section, we give conclusions and discussions.

2. New particles at the terascale

We study new particles at the terascale based on the following two assumptions.

One assumption is related to the grand unification. We assume that the values of gauge coupling constants g_i ($i = 1, 2, 3$) agree at the gravitational scale $M \equiv M_{\rm Pl}/\sqrt{8\pi} = 2.4 \times 10^{18}$ GeV ($M_{\rm Pl}$ is the Planck mass), and the gauge interactions are unified into a simple group. Then, the normalization of the hypercharge is fixed and the gauge coupling constant relating to $U(1)_Y$ is given by $g_1 = \sqrt{5/3}g'$, where g' is the gauge coupling constant of $U(1)_Y$ in the SM. The value of the unified one, $g_{\rm U}$, is supposed to be less than one, i.e., the theory is described as a weakly coupled system at M, for simplicity.

The other assumption is related to new particles and SUSY. We assume that there exist extra particles with the same gauge quantum numbers of SM fermions and/or their mirror particles around the terascale, that there is a big desert beyond the terascale until M, except for right-handed neutrinos (ν_R), and that the new colored particles form hypermultiplets as remnants of SUSY, which is broken down at M.

The solutions of renormalization group equations (RGEs) for g_i are expressed as

$$\alpha_i^{-1}(\mu) = \alpha_{\rm U}^{-1} + \frac{b_i}{2\pi} \ln \frac{M}{\mu}, \tag{1}$$

where $\alpha_i \equiv g_i^2/(4\pi)$, μ is a renormalization point (an arbitrary scale in the big desert), and b_i are coefficients of β functions at the one-loop level. In (1), we replace $\alpha_i^{-1}(M)$ with $\alpha_{\rm U}^{-1}$, using the unification conditions $\alpha_{\rm U} \equiv g_{\rm U}^2/(4\pi) = \alpha_i(M)$. Hereafter, we take the Z^0 gauge boson mass $M_Z (\doteqdot 91.19\,{\rm GeV})$ as μ, for simplicity.

By eliminating $\alpha_{\rm U}^{-1}$, the unification conditions are written as

$$b_i - b_j = \frac{2\pi[\alpha_i^{-1}(M_Z) - \alpha_j^{-1}(M_Z)]}{\ln(M/M_Z)},\ \ (i, j = 1, 2, 3). \tag{2}$$

By using the experimental values

$$\alpha_1^{-1}(M_Z) \doteqdot 59.01,\ \alpha_2^{-1}(M_Z) \doteqdot 29.57,\ \alpha_3^{-1}(M_Z) \doteqdot 8.446, \tag{3}$$

we obtain the relations

$$b_2 - b_3 \doteqdot 3.51,\ b_1 - b_2 \doteqdot 4.89,\ b_1 - b_3 \doteqdot 8.40. \tag{4}$$

In the presence of new particles, b_i are given by

$$b_1 = \frac{4}{3}N_f + \frac{1}{10}N_h + \frac{1}{30}n_Q + \frac{4}{15}n_U + \frac{1}{15}n_D + \frac{1}{10}n_L + \frac{1}{5}n_E, \tag{5}$$

$$b_2 = -\frac{22}{3} + \frac{4}{3}N_f + \frac{1}{6}N_h + \frac{1}{2}n_Q + \frac{1}{6}n_L, \tag{6}$$

$$b_3 = -11 + \frac{4}{3}N_f + \frac{1}{3}n_Q + \frac{1}{6}n_U + \frac{1}{6}n_D, \tag{7}$$

where N_f is the number of the family, N_h is the number of the Higgs doublet, and n_Q, n_U, n_D, n_L, and n_E are numbers of fields (counting that of a complex scalar field as one) with representations $(\mathbf{3}, \mathbf{2}, 1/6)$ or $(\overline{\mathbf{3}}, \mathbf{2}, -1/6)$, $(\overline{\mathbf{3}}, \mathbf{1}, -2/3)$ or $(\mathbf{3}, \mathbf{1}, 2/3)$, $(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$ or $(\mathbf{3}, \mathbf{1}, -1/3)$, $(\mathbf{1}, \mathbf{2}, -1/2)$ or $(\mathbf{1}, \mathbf{2}, 1/2)$, and $(\mathbf{1}, \mathbf{1}, 1)$ or $(\mathbf{1}, \mathbf{1}, -1)$ under $(SU(3)_C, SU(2)_L, U(1)_Y)$, respectively. The number of a Weyl fermion is considered to be double that of a complex scalar field, and that of a chiral supermultiplet is considered to be triple that of a complex scalar field. Hence, n_Q, n_U, and n_D should be multiples of 6, if new colored particles form hypermultiplets.

Using (4)–(7), we derive the relations

$$-n_Q + n_U + n_D - n_L \doteqdot 1.94(\simeq 2), \tag{8}$$

$$-7n_Q + 4n_U + n_D - n_L + 3n_E \doteqdot -35.65(\simeq -34), \tag{9}$$

$$3n_Q - n_U + n_D - n_L - 2n_E \doteqdot 27.0(\simeq 26), \tag{10}$$

where we take $N_f = 3$ and $N_h = 1$ according to the SM, and two of (8)–(10) are independent.

If we impose the condition $\alpha_{\mathrm{U}} \lesssim 1/10$ on α_{U} based on the assumption that g_{U} is less than one, we obtain the inequalities

$$n_Q + 8n_U + 2n_D + 3n_L + 6n_E \lesssim 121,\ 3n_Q + n_L \lesssim 38.5,\ 2n_Q + n_U + n_D \lesssim 40.0. \tag{11}$$

Using (8)–(11), we obtain *a unique solution*

$$n_Q = 6,\ n_U = 0,\ n_D = 12,\ n_L = 4,\ n_E = 0, \tag{12}$$

where we use values in parentheses in (8)–(10), for the sake of convenience, and require that n_Q, n_U, and n_D should be multiples of 6. The value of the unified gauge coupling constant is estimated as $\alpha_{\mathrm{U}} = \alpha_i(M) \sim 1/26$.

The uniqueness of (12) depends on our assumptions, which are not backed by very strong evidence. Other solutions are obtained by partially changing the assumptions. Here, we give typical examples.

(1) Change of unification scale: If we take $M_{\mathrm{U}} \simeq 10^{17}$ GeV in place of M, we obtain a solution $n_Q = 6$, $n_U = 0$, $n_D = 6$, $n_L = 0$, and $n_E = 2$ with $\alpha_{\mathrm{U}} \sim 1/31$.

(2) Change of normalization of $U(1)_Y$: If we take $g_1 = \sqrt{1.1}g'$ in place of $g_1 = \sqrt{5/3}g'$, we obtain a solution $n_Q = 0$, $n_U = 0$, $n_D = 6$, $n_L = 4$, and $n_E = 0$ with $\alpha_{\mathrm{U}} \sim 1/45$ and $M_{\mathrm{U}} = M$. On unification based on string models, the change of normalization is related to the choice of Kac–Moody level [12].

(3) Beyond the weakly coupled region: There is a solution $n_Q = 12$, $n_U = 12$, $n_D = 6$, $n_L = 4$, and $n_E = 0$ (or $n_Q = 12$, $n_U = 6$, $n_D = 12$, $n_L = 4$, and $n_E = 6$) with $\alpha_{\mathrm{U}} \sim 1/8.4$ and $M_{\mathrm{U}} = M$.

Furthermore, a variety of solutions are obtained if we relax the assumption that new colored particles form hypermultiplets. For example, there is a solution $n_Q = 6$, $n_U = 0$, $n_D = 8$, $n_L = 0$, and $n_E = 0$ with $\alpha_{\mathrm{U}} \sim 1/31$ and $M_{\mathrm{U}} = M$.

3. Theory at the terascale and beyond

We construct a theory including new particles without specifying its particle contents, to maintain generality.

The Lagrangian density of theory in a big desert is given by

$$\mathcal{L}_{\rm BSM} = \mathcal{L}_{\rm SM} + \sum_k (|D_\mu \phi^k|^2 - M_k^2 |\phi^k|^2) + \sum_d \overline{\psi}^d (i \not{D} + M_d) \psi^d \\ - \sum_k \lambda_k |\phi^k|^4 - \sum_{k<l} \lambda_{kl} |\phi^k|^2 |\phi^l|^2 - \sum_k \lambda'_k |\phi^k|^2 |H|^2 + \mathcal{L}_{\rm Ynew}, \tag{13}$$

where $\mathcal{L}_{\rm SM}$ is the SM one and new particles are denoted by ϕ^k and ψ^d. Here, ϕ^k represent complex scalar fields, ψ^d represent Dirac fermions $\psi^d = (\psi_L^d, \psi_R^d)$, H is the Higgs doublet of SM, $|\phi^k|^4 = (|\phi^k|^2)^2$, and $\mathcal{L}_{\rm Ynew}$ stands for Yukawa couplings such as $y'_{de} \overline{\psi}_L^d H \psi_R^e$ with a suitable assignment of the SM gauge quantum numbers.

Here, we present a conjecture that *the theory described by* (13) *is derived from a theory at* $M_{\rm U}$*, after the breakdown of unified gauge symmetry and SUSY, and a possible candidate is a unified theory with SUSY (partially including* $N = 2$ *structure for other sectors except for the SM matter sector) as an effective theory in the unbroken phase.*

First, we give a simple model to illustrate our idea. Let the relevant part of $\mathcal{L}_{\rm BSM}$ originate from the following Lagrangian density with $N = 2$ SUSY given in the unbroken phase:

$$\mathcal{L}_{\rm new}^{N=2} = \sum_{\rm R} (|D_\mu \Phi_{\rm R}|^2 - M_{\rm R}^2 |\Phi_{\rm R}|^2) + \sum_{\rm R} \overline{\Psi}_{\rm R} (i \not{D} + M_{\rm R}) \Psi_{\rm R} \\ - \frac{1}{2} g_{\rm U}^2 \sum_A \left(\sum_{\rm R} \Phi_{\rm R}^\dagger T^A \Phi_{\rm R} + i f^{ABC} \overline{\Phi}_{\rm Adj}^B \Phi_{\rm Adj}^C \right)^2 - 2 g_{\rm U}^2 \sum_A \left| \sum_{\rm R} \Phi_{\overline{\rm R}} T^A \Phi_{\rm R} \right|^2, \tag{14}$$

where $\Phi_{\rm R}$ and $\Psi_{\rm R}$ form a hypermultiplet with a representation R of a unified group $G_{\rm U}$ and $\Phi_{\rm Adj}^A$s are scalar fields that are members of gauge supermultiplets. The first term in the second line of (14) comes from the D-term, while the second one comes from the F-term relating to $\Phi_{\rm Adj}^A$. Note that a term such as $\Phi_{\overline{\rm R}} \Phi_{\rm Adj} \Phi_{\rm R}$ is gauge invariant and allowed in the superpotential, where $\overline{\rm R}$ is the complex conjugate representation of R.

Unless sizable contributions appear on the breakdown of symmetries, the theory has predictability for some coupling constants,[1] and our conjecture can be tested by studying the flow of various coupling constants under RGEs, where the initial values are fixed as

$$\alpha_i(M_{\rm U}) = \alpha_{\rm U},\ \lambda(M_{\rm U}) = c_\lambda \alpha_{\rm U},\ \lambda_k(M_{\rm U}) = c_k \alpha_{\rm U},\ \lambda_{kl}(M_{\rm U}) = c_{kl} \alpha_{\rm U}, \\ \lambda'_k(M_{\rm U}) = c'_k \alpha_{\rm U},\ y'_f(M_{\rm U}) = 0, \tag{15}$$

where c_λ, c_k, c_{kl}, and c'_k are model-dependent constants, e.g., $c_\lambda = 8\pi/25$ and $c_k = 24\pi/25$ for $G_{\rm U} = SU(5)$, and H and ϕ^k belong to the 5-plet and 10-plet, respectively. The y'_f are Yukawa coupling constants including $\mathcal{L}_{\rm Ynew}$. Note that any Yukawa couplings in $\mathcal{L}_{\rm Ynew}$ are not allowed at $M_{\rm U}$, though Yukawa couplings including gauginos exist in the unbroken phase. The fixing of coupling constants is due to the fact that the only interactions of hypermultiplets are gauge interactions if $N = 2$ SUSY is respected.

[1] Other types of unified theories, called finite unified theories, which have a large predictive power, have been proposed [13]. They are based on finiteness and the principle of reduction of coupling constants.

The RGE of λ (the quartic coupling constant of H) at the one-loop level is given by

$$\frac{d\lambda}{dt} = 24\lambda^2 - 6y_t^4 + 12\lambda y_t^2 - 3\lambda(g'^2 + 3g^2) + \frac{3}{8}[2g^4 + (g'^2 + g^2)^2] + T_{\text{new}}, \tag{16}$$

$$T_{\text{new}} = \sum_k a_k \lambda_k'^2 - \sum_f b_f y_f'^4 + \sum_{k,f} b_{kf} \lambda_k' y_f'^2, \tag{17}$$

where $t \equiv (1/16\pi^2)\ln(\mu/M_{\text{U}})$, y_t is the Yukawa coupling constant of the top quark, g is the gauge coupling constant of $SU(2)_L$, T_{new} stands for contributions from new particles, and a_k, b_f, and b_{kf} are model-dependent constants. It is interesting to find a model to derive $\lambda \doteqdot 0.131$.

If new particles couple to the SM fermions and the Higgs boson very weakly at the terascale, corrections to the SM predictions could be negligibly small and it could explain the agreement between the theoretical and experimental values based on the SM.

At this stage, the following questions are left unanswered. What is the origin of the weak scale, i.e. $v = 246\,\text{GeV}$? What is the origin of the new particles' masses at the terascale?

These can be explained by an extension with an extra $U(1)$ gauge symmetry ($U(1)_{\text{C}}$) and an SM singlet complex scalar field S. In this case, the following terms are added to $\mathcal{L}_{\text{BSM}}$:

$$\mathcal{L}_{\text{newS}} = |D_\mu S|^2 - M_S^2|S|^2 - \sum_k \lambda_{Sk}|S|^2|\phi^k|^2 - \lambda_{SH}|S|^2|H|^2 - \lambda_S|S|^4 \,. \tag{18}$$

By requiring that all hypermultiplets are massless at M_{U}, (14) is replaced by

$$\begin{aligned}\mathcal{L}_{\text{newC}}^{N=2} = &\sum_{\text{R}} |D_\mu \Phi_{\text{R}}|^2 + \sum_{\text{R}} \overline{\Psi}_{\text{R}} i \not{D} \Psi_{\text{R}} - \frac{1}{2} g_{\text{U}}^2 \sum_A \left(\sum_{\text{R}} \Phi_{\text{R}}^\dagger T^A \Phi_{\text{R}} + i f^{ABC} \overline{\Phi}_{\text{Adj}}^B \Phi_{\text{Adj}}^C \right)^2 \\ &- 2g_{\text{U}}^2 \sum_A \left| \sum_{\text{R}} \Phi_{\overline{\text{R}}} T^A \Phi_{\text{R}} \right|^2 - \frac{1}{2} g_{\text{C}}^2 \left(\sum_{\text{R}} q_{\text{R}} |\Phi_{\text{R}}|^2 + q_S|S|^2 \right)^2 - 2g_{\text{C}}^2 \left| \sum_{\text{R}} q_{\text{R}} \Phi_{\overline{\text{R}}} \Phi_{\text{R}} \right|^2,\end{aligned} \tag{19}$$

where g_{C} is the gauge coupling constant of $U(1)_{\text{C}}$, and q_{R} and q_S are the $U(1)_{\text{C}}$ charges of Φ_{R} and S, respectively.

The $\mathcal{L}_{\text{newC}}^{N=2}$ has a classical conformal invariance, and Bardeen's argument [14] of radiative corrections on masses can be applied to our theory. Strictly speaking, $\mathcal{L}_{\text{newC}}^{N=2}$ should be replaced by that in the broken phase. Our theory can be considered as an effective one relating massless string states; we assume that the breakdown of relevant symmetries is due to stringy effects and the masslessness of particles in $\mathcal{L}_{\text{BSM}}$ is protected against radiative corrections due to heavy particles of $O(M_{\text{U}})$, even in the broken phase, by string or finiteness magic [15].[2] This concept is different from the ordinary one. From the viewpoint of effective field theory, fine tuning of order $(M_k/M_{\text{U}})^2$ is required for each scalar field mass squared, M_k^2, at the terascale. We have a standpoint that such fine tuning might be an artifact in the effective field theory, which is caused by the observation that the effective theory does not completely describe the physics of fundamental theory.

[2] As the conformal invariance is explicitly broken in the presence of massive particles at M_{U}, the breakdown of $U(1)_{\text{C}}$ through the non-minimal coupling between S and gravity [16] does not occur.

From the matching condition between (13), (18), and (19), we obtain the relations

$$\alpha_i(M_{\rm U}) = \alpha_{\rm U},\ \lambda(M_{\rm U}) = c_\lambda \alpha_{\rm U} + 2\pi q_H^2 \alpha_{\rm C},\ \lambda_k(M_{\rm U}) = c_k \alpha_{\rm U} + 2\pi q_k^2 \alpha_{\rm C},$$
$$\lambda_{kl}(M_{\rm U}) = c_{kl}\alpha_{\rm U} + 2\pi q_k q_l \alpha_{\rm C},\ \lambda'_k(M_{\rm U}) = c'_k \alpha_{\rm U} + 2\pi q_H q_k \alpha_{\rm C},\ y'_f(M_{\rm U}) = 0,$$
$$\lambda_{SH}(M_{\rm U}) = 2\pi q_S q_H \alpha_{\rm C},\ \lambda_{Sk}(M_{\rm U}) = 2\pi q_S q_k \alpha_{\rm C},\ \lambda_S(M_{\rm U}) = 2\pi q_S^2 \alpha_{\rm C}, \tag{20}$$

where $\alpha_{\rm C} \equiv g_{\rm C}^2/(4\pi)$ and the contribution from the last term in (19) is omitted for simplicity.

In the SM, the electroweak symmetry is broken down with $m^2 < 0$ for the Higgs potential

$$V = m^2|H|^2 + \lambda|H|^4, \tag{21}$$

where $v = \sqrt{-m^2/2\lambda}$. In the case with $m^2(M_{\rm U}) = 0$ and $M_k^2(M_{\rm U}) = 0$, we obtain the relations

$$m^2 = \lambda_{SH}|\langle S\rangle|^2 \quad (\text{or } v = \sqrt{-\lambda_{SH}/2\lambda}|\langle S\rangle|),\ M_k^2 = \lambda_{Sk}|\langle S\rangle|^2, \tag{22}$$

where $\langle S\rangle$ is the VEV of S. Then, in order to derive $v = 246$ GeV and $M_k = O(1)$ TeV, we need the conditions

$$\lambda_{SH} < 0,\ \lambda_{Sk} > 0,\ |\lambda_{SH}| = O(1/10^2)|\lambda_{Sk}|,\ |\langle S\rangle| \neq 0. \tag{23}$$

A possible scenario to realize (23) is as follows.[3] After the coupling constants run from $M_{\rm U}$ with initial values $\lambda_{SH}(M_{\rm U}) \geq 0$, $\lambda_{Sk}(M_{\rm U}) > 0$, and $\lambda_S(M_{\rm U}) > 0$, S obtains a VEV via the Coleman–Weinberg mechanism [19], and $U(1)_{\rm C}$ is broken down around the terascale. Then, H and ϕ^k acquire the mass squared $m^2 = \lambda_{SH}|\langle S\rangle|^2$ and $M_k^2 = \lambda_{Sk}|\langle S\rangle|^2$, respectively. If λ_{SH} takes a negative value with a suitable magnitude around the weak scale, $SU(2)_L \times U(1)_Y$ can be broken down to $U(1)_{\rm EM}$. Furthermore, if λ_{Sk} take positive values with suitable magnitudes, ϕ^k have masses of $O(1)$ TeV. The positivity of M_k^2 requires $q_S q_k > 0$, and this means that ϕ^k possess a $U(1)_{\rm C}$ charge of the same sign as q_S. In order to generate masses of $O(1)$ TeV for other members of hypermultiplets, we need other sources without $N = 2$ SUSY structure. For example, we extend to a model with a singlet scalar field N and a singlet fermion $\tilde{N}$, which couple to members of hypermultiplets through Yukawa interactions as remnants of $N = 1$ SUSY. Then Dirac fermions acquire masses $M_d = f\langle N\rangle$, where f is a Yukawa coupling constant. λ_{Sk} for $q_S q_k < 0$ can also have positive values at the terascale due to radiative corrections if f is sufficiently large. It is also interesting to find a model to derive $v = 246$ GeV, $M_k = O(1)$ TeV, and $M_d = O(1)$ TeV.

4. Conclusions

We have predicted new particles at the terascale based on the assumptions that the standard model gauge interactions are unified around the gravitational scale with a big desert and new particles originate from hypermultiplets as remnants of supersymmetry, and have proposed a theoretical framework, which has predictability, at the terascale and beyond. The candidate of effective ultraviolet theory is a unified theory with (partial $N = 2$) SUSY and conformal invariance. To verify our framework, it is necessary to carry out model-dependent analysis and study its particle spectrum and phenomenology.

The following riddles remain unsolved. What is the origin of SM fermions? What is the origin of the hierarchical structure of Yukawa coupling constants?

Chiral superfields based on $N = 1$ SUSY might play an important role. Because a higher-dimensional space-time offers an environment in which both $N = 2$ and $N = 1$ SUSY coexist, there

[3] The basic idea is same as that in Refs. [17,18], where $U(1)_{B-L}$ plays the role of $U(1)_{\rm C}$.

is a prospect that SM particles and new particles originate from SUSY orbifold grand unified theories [20,21].

Hence, if predicted particles were discovered in the near future, there is a possibility that it would suggest the reality of three big paradigms in particle physics, i.e., grand unification, SUSY, and extra dimensions.

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