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Planck scale unification in a supersymmetric Standard Model

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Abstract

We show how gauge coupling unification near the Planck scale $M_p \sim 10^{19}$ GeV can be achieved in the framework of supersymmetry, facilitating a full unification of all forces with gravity. Below the conventional GUT scale $M_{\mathrm{GUT}} \sim 10^{16}$ GeV physics is described by a Supersymmetric Standard Model whose particle content is that of three complete **27** representations of the gauge group E_6. Above the conventional GUT scale the gauge group corresponds to a left–right symmetric Supersymmetric Pati–Salam model, which may be regarded as a "surrogate SUSY GUT" with all the nice features of $SO(10)$ but without proton decay or doublet–triplet splitting problems. At the TeV scale the extra exotic states may be discovered at the LHC, providing an observable footprint of an underlying E_6 gauge group broken at the Planck scale. Assuming an additional low energy $U(1)_X$ gauge group, identified as a non-trivial combination of diagonal E_6 generators, the μ problem of the MSSM can be resolved.

1. Introduction

Gauge coupling unification and the cancellation of quadratic divergences are two of the most appealing features of supersymmetric (SUSY) extensions of the Standard Model (SM) [1]. It is well known that the electroweak and strong gauge couplings extracted from LEP data and extrapolated to high energies using the renormalisation group (RG) evolution do not meet within the SM. However, in the framework of the minimal supersymmetric Standard Model (MSSM) [2] the couplings converge to a common value at some high energy scale. This allows one to embed SUSY extensions of the SM into Grand Unified Theories (GUTs), leading to SUSY GUTs based on $SU(5)$ or $SO(10)$.

However, despite their obvious attractions, SUSY GUTs face some serious challenges from the experimental limits on proton decay on the one hand, and the theoretical requirement of Higgs doublet–triplet splitting on the other as recently discussed for example in [3]. Furthermore the unification of gauge couplings near a conventional GUT scale $M_{\mathrm{GUT}} \sim 10^{16}$ GeV leaves open the question of a full unification of all the forces with gravity, although this may be achieved in the framework of string unification, including high energy threshold effects [4].

It was suggested some time ago that one should consider replacing the SUSY GUT theory by a Pati–Salam gauge group above $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, which plays the role of a "surrogate SUSY GUT" [5], since there is no proton decay or doublet–triplet splitting problem in such a theory. In this scheme the gauge couplings meet at $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, as in the MSSM, and are then held together up to the Planck scale by a combination of left–right symmetry and carefully selected matter content chosen so that the $SU(4)_{\mathrm{PS}}$ gauge group has the same beta function as the $SU(2)_L \times SU(2)_R$ gauge couplings [5]. However such "theoretical tuning" of the $SU(4)_{\mathrm{PS}}$ and $SU(2)_L \times SU(2)_R$ beta functions appears to be somewhat contrived.

Recently a so-called exceptional supersymmetric Standard Model (ESSM) has been proposed [6,7], in which the low energy particle content consists of three **27** representations of the gauge group E_6, plus in addition a pair of non-Higgs doublets H', $\bar{H}'$ arising from incomplete $\mathbf{27}'$, $\overline{\mathbf{27}}'$ representations. In the ESSM, gauge coupling unification works even better than in the MSSM [8]. Although the ESSM solves the usual μ problem via a singlet coupling to two Higgs doublets, the presence of the non-Higgs doublets H', $\bar{H}'$ introduces a new μ' problem since in this case a singlet coupling generating μ' is not

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readily achieved [6,7]. However the only purpose of including the non-Higgs states H', $\bar{H}'$ is to help achieve gauge coupling unification at $M_{\mathrm{GUT}} \sim 10^{16}$ GeV. This allows the possibility of removing the non-Higgs states H', $\bar{H}'$ from the spectrum. Of course the question of gauge coupling unification must then be addressed, which is the subject of the present Letter.

In this Letter we consider a similar model to the ESSM but without the additional non-Higgs doublets H', $\bar{H}'$. Clearly, without the additional non-Higgs doublets H', $\bar{H}'$, the gauge couplings will no longer converge at $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, or any other scale, so at first sight this possibility looks unpromising. However we shall show that, if the theory is embedded into a Pati–Salam theory at $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, then, remarkably, this leads to a unification of all forces with gravity close to the Planck scale. In the region between M_{GUT} and M_p there is not a SUSY GUT but a "surrogate SUSY GUT" based on the Pati–Salam gauge group which resolves the proton decay and doublet–triplet splitting problems of SUSY GUTs, with Planck scale unification achieved in a more natural way than in [5].

Unification in supersymmetric models containing one or three **27** representations of the gauge group E_6 has recently been considered in the literature [9]. Assuming an intermediate Pati–Salam gauge group at the scale 10^{15} GeV at which the Standard Model (SM) couplings satisfy $\alpha_1 = \alpha_2$, it was claimed that the resulting Pati–Salam gauge couplings could subsequently meet at a higher scale about 10^{18} GeV [9]. However the condition $\alpha_1 = \alpha_2$ cannot be consistently applied at the Pati–Salam breaking scale. Instead we find the Pati–Salam breaking scale to be about an order of magnitude larger than the crossing point $\alpha_1 = \alpha_2$, close to $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, with full unification close to $M_p \sim 10^{19}$. Planck scale unification has also been considered in non-supersymmetric models in [10]. In our analysis we shall naively extrapolate the two-loop RGEs up to M_p, although in reality we expect new physics effects arising from quantum gravity to set in about an order of magnitude below this. For example, although the Planck scale is usually equated with the Planck mass energy scale M_p given by $M_p = \sqrt{\hbar c/G} \approx 1.2 \times 10^{19}\ \mathrm{GeV}/c^2$ where G is Newton's constant, the scale at which quantum gravity becomes relevant may be considered to be $(8\pi G)^{-1/2} \approx 2.4 \times 10^{18}$ GeV, where the factor of 8π comes from the Einstein field equation $G^{\mu\nu} = 8\pi G T^{\mu\nu}$, which is sometimes referred to as the reduced Planck scale. It is around this energy scale that an effective quantum field theory of gravity is expected to break down and some new physics takes over since effective quantum field theories of gravity contain corrections to the predictions of General Relativity proportional to powers of E^2/M_p^2 where E is the energy scale of interest. A more precise estimate of the energy scale at which new physics associated with quantum gravity takes over, based on unitarity violation, may be found in [11], and we return to this point later.

The layout of the rest of this Letter is as follows. In the Section 2 we consider the pattern of symmetry breaking assumed in this Letter. In Section 3 we consider the two loop RG evolution of gauge couplings in this model from low energies, through the Pati–Salam breaking scale at $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, assuming various Pati–Salam breaking Higgs sectors, and show that the Pati–Salam gauge couplings converge close to the Planck scale $M_p \sim 10^{19}$ GeV. In Section 4 we shall construct an explicit supersymmetric model of the kind we are considering. Finally we conclude the Letter in Section 5.

2. Pattern of symmetry breaking

The two step pattern of gauge group symmetry breaking we analyse in this Letter is:

$$E_6 \overset{M_p}{\overbrace{\longrightarrow}} G_{422} \otimes D_{LR} \overset{M_{\mathrm{GUT}}}{\overbrace{\longrightarrow}} G_{321} \tag{1}$$

where the gauge groups are defined by:

$$\begin{aligned} &G_{422} \equiv SU(4) \otimes SU(2)_L \otimes SU(2)_R, \\ &G_{321} \equiv SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \end{aligned} \tag{2}$$

and we have assumed that the first stage of symmetry breaking happens close to the Planck scale and the second stage happens close to the conventional GUT scale. The first stage of symmetry breaking is based on the maximal E_6 subgroup $SO(10) \otimes U(1)_\psi$ and the maximal $SO(10)$ subgroup $G_{422} \otimes D_{LR}$ corresponding to a Pati–Salam symmetry with D_{LR} being a discrete left–right symmetry. [1]

The pattern of symmetry breaking assumed in this Letter is different from that commonly assumed in the literature based on the maximal $SO(10)$ subgroup $SU(5) \otimes U(1)_\chi$ [6,7,13]. In particular the Pati–Salam subgroup does not contain the Abelian gauge group factor $U(1)_\chi$. The only Abelian gauge group factor involved in this pattern of symmetry breaking is $U(1)_\psi$, and in the present analysis we assume that this is broken at M_p. However, as discussed in Section 4, there are good phenomenological motivations, related to the solution to the μ problem, for preserving a low energy $U(1)'$ gauge group, and this would require the $U(1)_\psi$ gauge group to be preserved. In the present Letter we do not consider the effect of including the $U(1)_\psi$ gauge group factor in the RG analysis, however we have checked that Planck scale unification would still be possible, so the results presented here would not be much affected by its inclusion.[2]

The first stage of symmetry breaking close to M_p will not be considered in this Letter. We only remark that the Planck scale theory may or may not be based on a higher dimensional string theory. Whatever the quantum gravity theory is, it will involve some high energy threshold effects, which will depend on the details of the high energy theory, and which we do not consider in our analysis.

The second stage of symmetry breaking close to M_{GUT} is within the realm of conventional quantum field theory, and requires some sort of Higgs sector, in addition to the assumed matter content of three **27** representations of the gauge

[1] Under D_{LR} the matter multiplets transform as $q_L \to q_L^c$, and the gauge groups $SU(2)_L$ and $SU(2)_R$ become interchanged [12].

[2] With $U(1)_\psi$ included in the RG analysis for the $\mathbf{27_H} + \overline{\mathbf{27}}_\mathbf{H}$ graph (right panel of Fig. 1) it may be necessary to increase the effective MSSM threshold to 350 GeV to ensure Planck scale unification for the larger experimental values of the strong coupling constant.