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Small extra dimensions from the interplay of gauge and supersymmetry breaking

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Abstract

Higher-dimensional theories provide a promising framework for unified extensions of the supersymmetric Standard Model. Compactifications to four dimensions often lead to $U(1)$ symmetries beyond the Standard Model gauge group, whose breaking scale is classically undetermined. Without supersymmetry breaking, this is also the case for the size of the compact dimensions. Fayet–Iliopoulos terms generically fix the scale M of gauge symmetry breaking. The interplay with supersymmetry breaking can then stabilize the compact dimensions at a size $1/M$, much smaller than the inverse supersymmetry breaking scale $1/\mu$. We illustrate this mechanism with an $SO(10)$ model in six dimensions, compactified on an orbifold.

1. Introduction

Higher-dimensional theories provide a promising framework for unified extensions of the supersymmetric Standard Model [1]. Interesting examples have been constructed in five and six dimensions compactified on orbifolds [2–7], which have many phenomenologically attractive features. During the past years it has become clear how to embed these orbifold GUTs into the heterotic string [8–10], separating the GUT scale from the string scale on anisotropic

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orbifolds [11]. A class of compactifications yielding supersymmetric Standard Models in four dimensions (4D) have been successfully constructed [12–14].

For a given orbifold compactification of the heterotic string, one can consider different orbifold GUT limits where one or two of the compact dimensions are larger than the other five or four, respectively [10]. One then obtains an effective five-dimensional (5D) or six-dimensional (6D) GUT field theory as intermediate step between the full string theory and the supersymmetric Standard Model. We shall focus on 6D field theories compactified on $T^2/\mathbb{Z}_2$ with two Wilson lines. These models have four fixed points where quantum corrections generically induce Fayet–Iliopoulos terms [15,16]. In the case of the heterotic string the magnitude of these local terms is $\mathcal{O}(M_{\mathrm{GUT}})$, which suggests that they may lead to a stabilization of the compact dimensions at $R \sim 1/M_{\mathrm{GUT}}$ [16].

Quantum corrections to the vacuum energy density, the Casimir energy, play a crucial role in the stabilization of compact dimensions [17]. Various aspects of the Casimir energy for 6D orbifolds have already been studied in [18–20]. Stabilization of the volume can be achieved by means of massive bulk fields, brane localized kinetic terms or bulk and brane cosmological terms [18]. Alternatively, the interplay of one- and two-loop contributions to the Casimir energy can lead to a stabilization at the length scale of higher-dimensional couplings [21]. In addition, fluxes and gaugino condensates play an important role [22,23].

In this paper we consider orbifold GUTs, which generically have two mass scales: $M \sim M_{\mathrm{GUT}}$, the expectation value of bulk fields induced by local Fayet–Iliopoulos terms, and $\mu \ll M_{\mathrm{GUT}}$, the scale of soft supersymmetry breaking mass terms. As we shall see, the interplay of 'classical' and one-loop contributions to the vacuum energy density can stabilize the extra dimensions at small radii, $R \sim 1/M_{\mathrm{GUT}} \ll 1/\mu$ with bulk energy density $\mathcal{O}(\mu^2 M_{\mathrm{GUT}}^2)$. We shall illustrate this mechanism with an $SO(10)$ model in six dimensions [24] which together with gaugino mediation [25,26] is known to lead to a successful phenomenology [27,28].

The paper is organized as follows. In Section 2 we briefly describe the relevant features of the 6D orbifold GUT model. The Casimir energies of scalar fields with different boundary conditions are discussed in Section 3. These results are used in Section 4 to evaluate the Casimir energy of the considered model. In Section 5 the stabilization mechanism is described. Appendices A and B deal with the mode expansion on $T^2/\mathbb{Z}_2^3$ and the evaluation of Casimir sums, respectively.

2. The model

As an example, we consider a 6D $\mathcal{N}=1$ $SO(10)$ gauge theory compactified on an orbifold $T^2/\mathbb{Z}_2^3$, corresponding to $T^2/\mathbb{Z}_2$ with two Wilson lines [24]. The model has four inequivalent fixed points ('branes') with the unbroken gauge groups $SO(10)$, the Pati–Salam group $G_{\mathrm{PS}} = SU(4) \times SU(2) \times SU(2)$, the extended Georgi–Glashow group $G_{\mathrm{GG}} = SU(5) \times U(1)_X$ and flipped $SU(5)$, $G_{\mathrm{fl}} = SU(5)' \times U(1)'$, respectively. The intersection of these GUT groups yields the Standard Model group with an additional $U(1)$ factor, $G'_{\mathrm{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$, as unbroken gauge symmetry below the compactification scale. At the fixed points only 4D $\mathcal{N}=1$ supersymmetry remains unbroken. Gauge and supersymmetry breaking are realized by assigning different parities to the different components of the **45**-plet of $SO(10)$, which is a 6D $\mathcal{N}=1$ vector multiplet containing 4D $\mathcal{N}=1$ vector (V) and chiral (Σ) multiplets (cf. Table 1).

The model has three **16**-plets of matter fields, localized at the Pati–Salam, the Georgi–Glashow, and the flipped $SU(5)$ branes. Further, there are two **16**-plets, ϕ and ϕ^c and two **10**-plets, H_5 and H_6 of bulk matter fields. Their mixing with the brane fields yields the characteristic flavor structure of the model [24,28].