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Power law scaling in universal extra dimension scenarios

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Abstract

We study the power law running of gauge, Yukawa and quartic scalar couplings in the universal extra dimension scenario where the extra dimension is accessed by all the standard model fields. After compactifying on an S_1/Z_2 orbifold, we compute one-loop contributions of the relevant Kaluza–Klein (KK) towers to the above couplings up to a cutoff scale Λ. Beyond the scale of inverse radius, once the KK states are excited, these couplings exhibit power law dependence on Λ. As a result of faster running, the gauge couplings tend to unify at a relatively low scale, and we choose our cutoff also around that scale. For example, for a radius $R \sim 1\ \text{TeV}^{-1}$, the cutoff is around 30 TeV. We then examine the consequences of power law running on the triviality and vacuum stability bounds on the Higgs mass. We also comment that the supersymmetric extension of the scenario requires R^{-1} to be larger than $\sim 10^{10}$ GeV in order that the gauge couplings remain perturbative up to the scale where they tend to unify.

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1. Introduction

In the standard model (SM), the gauge, Yukawa and quartic scalar couplings run logarithmically with the energy scale. Although the gauge couplings do not all meet at a point, they tend to unify near 10^{15} GeV. Such a high scale is beyond the reach of any present or future experiments. Extra dimensions accessible to SM fields have the virtue, thanks to the couplings' power law running, of bringing the unification scale down to an explorable range. Higher-dimensional theories, with radii of compactification around an inverse TeV, have been investigated from the perspective of high energy experiments, phenomenology, string theory, cosmology, and astrophysics. Such TeV scale extra-dimensional scenarios could lead to a new mechanism of supersymmetry breaking [1], address the issue of fermion mass hierarchy from a different angle [2], provide a cosmologically viable dark matter candidate [3], interpret the Higgs as a quark composite leading to a successful electroweak symmetry breaking without the necessity of a fundamental Yukawa interaction [4], and, as mentioned before and what constitutes the central issue of our present study, lower the unification scale down to a few TeV [5,6]. Our concern here is a specific framework, called the universal extra dimension (UED) scenario, where there is a single flat extra dimension, compactified on an S_1/Z_2 orbifold, which is accessed by all the SM particles [7]. From a 4-dimensional viewpoint, every field will then have an infinite tower of Kaluza–Klein (KK) modes, the zero modes being identified as the SM states. We examine the cumulative contribution of these KK states to the renormalisation group (RG) evolution of the gauge, Yukawa and quartic scalar couplings. Our motive is to extract any subtle features that emerge due to the KK tower induced power law running of these couplings in contrast to the usual logarithmic running of the standard 4-dimensional theories, and whether they set any limit on parameters for the sake of theoretical and experimental consistency. Before we illustrate the RG calculational details, we take a stock of the existing constraints on the UED scenario, and we comment on what does RG evolution technically mean in the context of *hitherto* non-renormalisable higher-dimensional theories.

The key feature of UED is that the momentum in the universal fifth direction is conserved. From a 4-dimensional perspective this implies KK number conservation. Strictly speaking, what actually remains conserved is the KK parity $(-1)^n$, where n is the KK number. As a result, the lightest KK particle is stable. Also, KK modes cannot affect electroweak processes at the tree level. They do however contribute to higher order electroweak processes. In spite of the infinite multiplicity of the KK states, the KK parity ensures that all electroweak observables are finite (up to one-loop),[1] and comparison of the observable predictions with experimental data yields bounds on R. Constraints on the UED scenario from $g-2$ of the muon [8], flavour changing neutral currents [9–11], $Z \to b\bar{b}$ decay [12], the ρ parameter [7,13], several other electroweak precision tests [14] and implications from hadron collider studies [15], all conclude that $R^{-1} \gtrsim 300$ GeV.

We now come to the technical meaning of RG running in a higher-dimensional context. This has been extensively clarified in [5] in a general context, and here we merely reiterate it to put our specific calculations into perspective. Like all other extra-dimensional models, from a 4-dimensional point of view, the UED scenario too is non-renormalisable due to the infinite multiplicity of the KK states.[2] So 'running' of couplings as a function of the energy scale μ

[1] The observables start showing cutoff sensitivity of various degree as one goes beyond one-loop or considers more than one extra dimension.

[2] For a study of ultraviolet cutoff sensitivity in different kinds of TeV scale extra-dimensional models, see [16].