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Lattice gauge theory approach to spontaneous symmetry breaking from an extra dimension

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Abstract

We present lattice simulation results corresponding to an $SU(2)$ pure gauge theory defined on the orbifold space $E_4 \times I_1$, where E_4 is the four-dimensional Euclidean space and I_1 is an interval, with the gauge symmetry broken to a $U(1)$ subgroup at the two ends of the interval by appropriate boundary conditions. We demonstrate that the $U(1)$ gauge boson acquires a mass from a Higgs mechanism. The mechanism is driven by two of the extra-dimensional components of the five-dimensional gauge field which play respectively the role of the longitudinal component of the gauge boson and a massive real physical scalar, the Higgs particle. Despite the non-renormalizable nature of the theory, we observe only a mild cut-off dependence of the physical observables. We also show evidence that there is a region in the parameter space where the system behaves in a way consistent with dimensional reduction.

1. Introduction

Spontaneous symmetry breaking (SSB) is the phenomenon where the ground state of a system does not access all of its available symmetry, apparently breaking the symmetry group to a subgroup. In the Standard Model (SM) this is a crucial mechanism and it is not only responsible for predicting the existence of a fundamental scalar field, the Higgs particle, but also for the gauge bosons and fermions acquiring a mass. The somewhat unsatisfactory fact about this mechanism in the SM, is that the Higgs potential, which is the concrete object that drives SSB, is input by

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hand at tree level in the Lagrangian, simply because we do not have any more fundamental way to generate it. There are many ideas of course trying to suggest an origin for the Higgs and its potential, one of the most elegant being that the Higgs field is the extra-dimensional component of a higher dimensional gauge field and that the potential is generated quantum mechanically [1]. The earliest scenarios considered as extra-dimensional space the sphere S^2 [2–5]. In later applications the extra-dimensional space was taken to be non-simply connected, like S^1 or T^2 [6–8], so that the (non-contractible) Polyakov loops are non-trivial. This is the general context where we would like to put ourselves in the present work. Alternative ways to achieve SSB in gauge theories with extra dimensions are discussed in [9,10].

There are enough motivations to take this idea seriously besides the economic way of generating the Higgs with its potential but the property that drew a lot of recent attention to these theories is the so-claimed attractive possibility of all order finiteness of the physical scalar mass. This sounds like a paradox from the beginning since the very point which has kept many field theorists rather hesitant from taking such an idea seriously is that higher (than four) dimensional gauge theories are non-renormalizable and in a typical non-renormalizable theory one would expect that a mass parameter receives quantum corrections appearing in an arbitrary power of some dimensionless quantity built out of a dimensionful coupling and the cut-off. This is to be compared with the renormalizable SM where the couplings are dimensionless and the Higgs mass receives only a quadratic ultra-violet (UV) cut-off dependence under quantum corrections. Since even this quadratic UV sensitivity has been viewed as a drawback, supersymmetric generalizations of the SM were introduced and analyzed in detail, where the power like cut-off sensitivity is not present due to cancellations of infinities between superpartners. There is no doubt that supersymmetry is an elegant solution to the problem but it could happen that it is not realized at energies accessible in near future collider experiments so it is useful to be aware of alternative solutions. Back then to extra dimensions, in the case where the extra (fifth here) dimension is compactified on a circle, one can carry out a one-loop calculation of the Higgs mass and verify its aforementioned finiteness [11,12] and can even give all order arguments to that effect [13–20], but the problem with this solution is that a simple circle compactification cannot be realistic for various reasons, the absence of chiral fermions being one of the main.

A way out is to compactify the extra dimension on an interval I_1 instead of a circle, which can support chiral fermions at the two ends of the interval. Since the interval can be obtained easily from the circle by "orbifolding", i.e. by identifying points and fields in the circle theory under the Z_2 reflection operator $\mathcal{R}: x^5 \to -x^5$, we will use the name orbifold when we refer to such a theory. A characteristic property of this orbifold is that it is defined on a space with two four-dimensional boundaries at each of the fixed points of the reflection action, where the gauge symmetry is reduced, thus naturally differentiating the boundaries from the rest of the space, which we call the bulk. An unfortunate consequence of field theories defined in such spaces is that the all order finiteness of the Higgs mass arguments are not anymore applicable because of the bulk-boundary interactions appearing at higher orders in perturbation theory which start to infect the finite bulk mass with cut-off dependence [21]. This is not unexpected; it is known that handling non-renormalizable theories analytically is not easy, in fact there is no general prescription that can be used in these theories such that their predictions are trustworthy.

We would therefore like here to start a systematic investigation of higher dimensional orbifold gauge theories from the point of view of a lattice regularization [17,22,23]. The theory which will serve as our concrete example is an $SU(2)$ gauge theory which has the symmetry broken (by boundary conditions) to its $U(1)$ subgroup on the boundaries. This, we will argue, is a promising way of approaching extra-dimensional theories: the goal is a non-perturbative