Physics of Extra Dimensions

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Csaba Csáki
Newman Laboratory of Elementary Particle Physics
Cornell University
Ithaca, NY 14853
phone: 607-254-8935
e-mail: csaki@lepp.cornell.edu

Below we give a short summary of the achievements related to the physics of extra dimensions that resulted from research partly funded by this project.

Higgsless electroweak symmetry breaking

The main goal for particle physics of the next decade is to understand the origin of electroweak symmetry breaking. I have devoted quite a lot of time over the past six years to try to study this issue in the context of extra dimensions. In 2003, we have made a completely new proposal for a mechanism of electroweak symmetry breaking, which does not involve the existence of a physical Higgs scalar at all. In these theories called "higgsless models" electroweak symmetry is broken by the boundary conditions at the boundary of the extra dimension, rather than by the VEV of a physical Higgs. That such a thing may be possible was first hinted at in our paper [1] with Grojean (Saclay), Murayama (Berkeley), Pilo (Saclay) and Terning (Los Alamos) where we have investigated the nature of gauge symmetry breaking via boundary conditions in extra dimensional theories. We have calculated the energy dependence of the scattering amplitudes of massive gauge bosons in such theories, and found that as expected the amplitudes that grow with energy cancel in theories where there is no explicit gauge symmetry breaking terms, while the growing modes remain if any explicit gauge symmetry breaking term is present. This may yield a new possibility for electroweak symmetry breaking without a Higgs scalar, since it shows that Kaluza-Klein theories can circumwent the old theorems that required the presence of a physical Higgs for unitarization of the scattering amplitudes of massive gauge bosons. After this, we have found [2] a model that comes very close to being a realistic theory. It has custodial SU(2) preserved due to putting an $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ in the bulk of 5D anti-de Sitter space. The leading expressions of the W and Z masses are the correct SM expressions. We have also examined in the paper [3] the issue of how to include fermions and fermion masses into such theories. We found that it is quite possible to simultaneously give quarks and leptons a mass via boundary conditions, and that a realistic mass spectrum can be obtained. The main question about these models eventually is if they are able to reproduce the precision predictions of the SM which have been verified at LEP. We have calculated the leading corrections to the electroweak precision observables in [4], and found that generically the S-parameter is too large. In our most recent work over the past year we have found a simple way to get around the constraint from the electroweak precision observables. The calculation in [4] of the S-parameter implicitely assumed, that the fermions are localized on the TeV brane. However, we have shown in [5] that if one relaxes this requirement, then the S-parameter can be significantly reduced. In fact, if one assumes that the wave functions of the fermions are exactly flat, the S-parameter is reduced by a factor of 3, just to the edge of the experimentally allowed region. With some further tuning of the shape of the fermion wave functions the S-parameter can be made completely vanishing. The only remaining obstacle was the incorporation of a heavy top quark for which two different solutions were presented. With Cornell student Reece Csáki suggested [16] that the third generation quarks could be special because they may live in a different warped throat (which also led to investigating general multi-throat setups [11] within field theory). The second proposal [10] was to use new representations under the custodial symmetry to protect the $Zb\bar{b}$ vertex from large corrections. A simple modification of Higgsless models [8] is to consider the setup with a bulk Higgs that is sharply peaked on the UV brane, but whose VEV can be much larger than the SM VEV. These models interpolate between the SM, the RS1 approach and the Higgsless models, and the Higgs can have very peculiar properties, in particular supressed but measurable couplings to SM gauge bosons (”gauge-phobic Higgs”).

Gauge-higgs unification

Another possibility for using extra dimensions is to provide a new way of protecting the Higgs mass from large quantum corrections. This would happen if the Higgs was a part of the higher dimensional gauge multiplet, which in addition to the 4D vector field would also contain 4D scalars. In this case the higgs mass would really be protected from large correction via higher dimensional gauge invariance. This idea was first proposed a long time ago by Manton, and Csáki has re-examined such models recently. First, he was applying this idea to six dimensional orbifold models [19], and then together with Cornell post-docs Cacciapaglia and Park presented [12] a complete model in five dimensions model that would have these properties, and where both the Higgs and the top could be sufficiently heavy.

Holographic QCD and technicolor

Another interesting application of extra dimensions is to study warped extra dimensional models as holographic duals to QCD or other strongly interacting gauge theories (AdS/QCD). Together with Cornell student Reece Csáki showed [9] how to properly include the effect of a non-trivial gluon condensate into this setup, and how implement asymptotic freedom into these theories. They have also used the tools to argue that no holographic dual to a strongly interacting gauge theory will give a negative S-parameter if it gives rise to dynamical electroweak symmetry breaking [7].

Chiral lattice theory from warped domain wall fermions

When considering the higgsless models as discussed above, we have noticed that the gauge boson mass spectrum has a peculiar proerty: the lightest KK mode is much lighter than the ordinary KK scale of the model. This means that these types of models could be used to separate out mass scale of KK fermions and KK gauge bosons. The reason why this could be interesting is that this may get around the problem of how to eliminate the unwanted degrees modes in domain wall fermion constructions for chiral lattice gauge theories. In [17] we have found a construction which at the classical level gives a chiral lattice gauge theory starting only from vectorlike fermions. It is a generalization of Kaplan's domain wall approach but in warped space rather than the usual flat space, using the higgsless limit of this theory. While it is clear that the classical theory will be chiral, since in the appropriate limit some modes will become strongly coupled only a full-fledged lattice simulation will be able to decide whether the actual quantum theory remains chiral or not.

Other professional activities during 2001-2007

I had five graduate students at Cornell, Jay Hubisz, Patrick Meade, Matt Reece, Johannes Heinonen and David Curtin. Jay moved to Fermilab as a post-doc, Patrick to Harvard (and now on to the IAS with Nima Arkani-Hamed). Matt is graduating this coming summer and already has a lot of post-doc offers. Johannes and David are current students. I have given lectures at TASI 2002 and 2004, at the ICTP summer school in 2007, at Cargese 2007, at the Taiwain spring school in 2006 and the Shanghai string school in 2005. I was plenary speaker at Quarks 2004, 2006, SUSY 2004 and Planck 2003, 2005 and 2007. I am a co-organizer of a workshop at the Aspen Ctr. for Physics in the summer of 2005. I have refereed for several journals.

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