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PHENOMENOLOGY OF HIGGSLESS ELECTROWEAK SYMMETRY BREAKING

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It is possible to construct models based on warped extra dimensions in which electroweak symmetry breaking takes place without the introduction of any Higgs fields. This breaking can occur through the judiciuous choice of boundary conditions applied to gauge fields living in the bulk. One then finds that the fifth components of these bulk fields act as the Goldstone bosons, even for the would-be zero modes of the Kaluza-Klein tower. In this talk I will discuss the phenomenology of such scenarios, in particular, the problems associated with the construction of realistic models due to the simultaneous constraints imposed by precision electroweak data, present collider search limits and the requirement of perturabtive unitarity in $W_L^+ W_L^-$ elastic scattering. Future collider signatures for such scenarios are also discussed.

In the SM the conventional Higgs doublet plays several roles, in particular, generating the fermion as well as the W/Z masses with $\rho = 1$ and insuring perturbative unitarity (PU) in, *e.g.*, $W_L^+ W_L^-$ scattering. We can, however, easily imagine electroweak symmetry breaking (EWSB) mechanisms wherein things are not quite so simple. One of the latest attempts[1] at describing EWSB makes use of generalized boundary conditions (BC's) in a 5-d warped, Higgsless Left-Right Symmetric model. Such a breaking of gauge symmetries as happens in these models cannot occur in the case of the usual orbifold BC's due to, *e.g.*, the periodicity requirement. In addition, the usual BC's imposed on the 4-d components of a bulk gauge field, $\partial A_\mu| = 0$, forces the wavefunction for the lightest mode to be flat in the extra dimension and therefore the corresponding state to be massless thus leaving all gauge symmetries unbroken. Of course the choice of BC's is not arbitrary and must be consistent with, *e.g.*, the variation of the action.

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For such a scenario to be successful it must a mechanism to do all that the Higgs does without the introduction of additional scalars. Fortunately, this scenario indeed gives rise to a pattern of masses and couplings for gauge fiels which is qualitatively very similar to the usual SM with a doublet Higgs. In this Randall-Sundrum type setup the BC's are specifically chosen to break $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ on the Planck brane with the subsequent breaking $SU(2)_L \times U(1)_Y \to U(1)_{QED}$ on the TeV brane. After the Planck scale symmetry breaking occurs, a global $SU(2)_L \times SU(2)_R$ symmetry remains in the brane picture; this breaks on the TeV-brane to a diagonal group $SU(2)_D$ corresponding to the custodial $SU(2)$ symmetry present in the SM. This custodial $SU(2)_D$ helps maintain the tree level $\rho = 1$ result. We note that in general such a model contains a large number of parameters: an overall mass scale, the 3 gauge couplings, $g_{L,R,B}$, and also four parameters describing the various gauge field kinetic terms, localized on the two 3-branes, which we denote as $\delta_{B,D,L,Y}$. At tree level, two of the gauge couplings as well as the mass scale are fixed by the values of G_F and $M_{W,Z}$, which we use as input, while the remaining ratio, $\kappa = g_R/g_L$, is found to be restricted to values not far from unity by various detailed model considerations. In pricipal, the brane terms remain unrestricted.

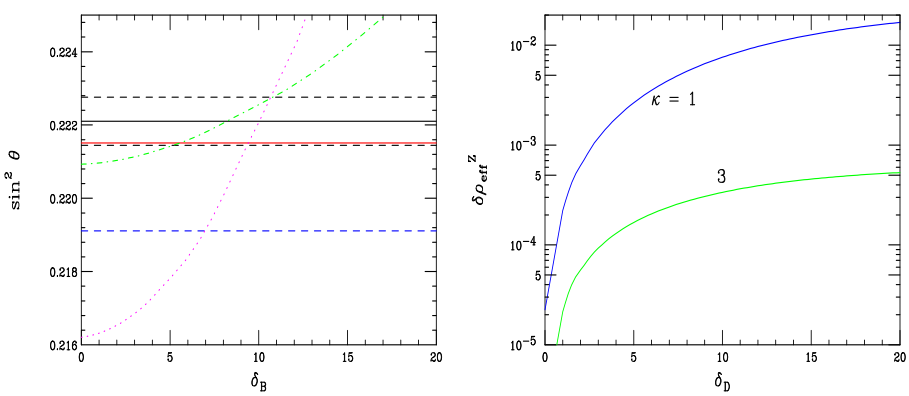

Figure 1: (Left) $\sin^2\theta$ for each of the three definitions as a function of δ_B. The black horizontal solid and dashed curves correspond to the on-shell value $\pm 1\sigma$, the solid red (dashed blue) curve represents $\sin^2\theta_{eff}$ for $\kappa = 3(1)$ while the dot dashed green (dotted magenta) curve is for $\sin^2\theta_{eg}$. We illustrate the effects of including the $U(1)_{B-L}$ brane kinetic term. (Right) $\delta\rho^Z_{eff}$ as a function of the $SU(2)_D$ brane term δ_D for $\kappa = 1$ and 3.

Unfortunately, as we will discuss below, a completely realistic model of this kind has yet to be constructed due to the tensions between the various

constraints that need to be satisfied. Not only must the correct pattern of EWSB be obtained but we also demand PU while not permitting the gauge boson excitations to be sufficiently light or strongly coupled to have shown up at the Tevatron or indirectly in contact interaction searches at LEP II. Recall that in the SM without a Higgs, PU violation in $W_L^+ W_L^-$ elastic scattering occurs at $\sqrt{s} \simeq 1.8$ TeV and thus we must expect light neutral KK states significantly below this mass scale to compensate for the lack of a Higgs.

An example of one such tension problem in the present scheme is the existence of 3 different $\sin^2\theta$'s in this model all of which are identical in the SM at tree level: $\sin^2\theta_{OS} = 1 - M_W^2/M_Z^2$, which is fixed by the input parameters, as well as $\sin^2\theta_{eg} = e^2/g_W^2$ and $\sin^2\theta_{eff}$ as defined on the Z pole. An example of this is shown in Fig. 1; clearly for a successful model we must require that all three of these parameters take on very similar values which greatly reduces the size of the allowed parameter space. Similarly, we must demand that deviations of the ρ parameter from unity as defined, *e.g.*, through the Z couplings, must also be small. As we see in another example shown in Fig. 1 this too constrains the parameter space as we would want $\delta\rho$ to be less than, say, $\sim few\ 10^{-3}$. In this simple example this would imply that δ_D not be too large. It is important to observe that this set of three quantities; $\delta\rho$ and $\sin^2\theta_{eg,eff}$ can be used to describe all of the deviations from the tree level SM in precision measurements.

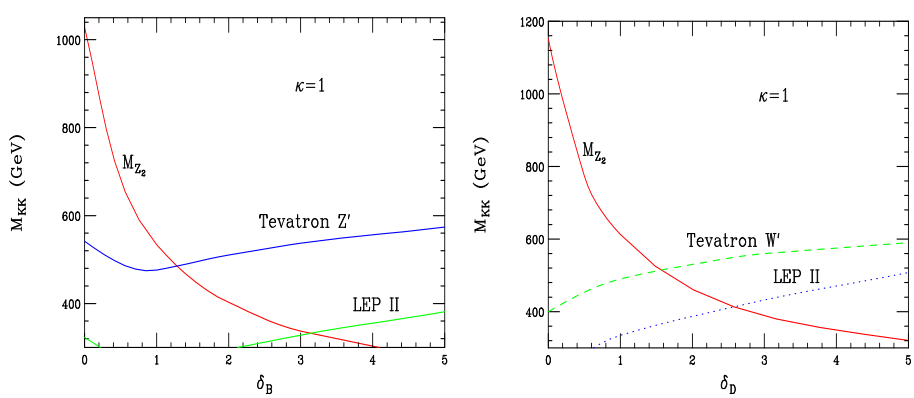

Figure 2: (Left) The predicted mass of the lightest KK excitation, the lower bound on the mass from the Run II Tevatron Z' searches as well as the lower bound from LEPII as a function of δ_B; (Right) Same as before but now for a non-zero δ_D and employing the Run I Tevatron bound from W' searches.

The next set of constraints arises from failed searches at the Tevatron for the charged and neutral KK excitations, analogous to W' and Z' searches,

respectively, as well as contact interaction bounds from LEP II. Sample constraints on the Higgsless model parameter space arising from these considerations are shown in Fig. 2. Here we see that these constraints tend to favor small values for the δ_i parameters corresponding to larger KK masses while the 'matching' of the three $\sin^2\theta$'s tend to favor larger values for these brane terms.

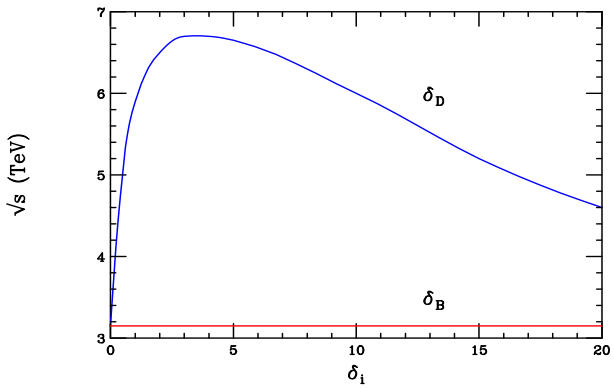

Figure 3: The scattering energy at which perturbative unitarity is violated in $W_L^+W_L^-$ scattering as a function of the kinetic terms. We take $\kappa = 1$ in this plot.

A last consideration is PU and its violation in $W_L^+W_L^-$ scattering. In the SM the individual diagrams consisting only of gauge bosons each lead to amplitudes which grow $\sim s^2$; gauge invariance removes this growth when the diagrams are summed yielding a $\sim s$ growth. At this point the Higgs contribution enters removing this growth leaving only constant terms and results in PU. Here, with no Higgs, the W 4-point and WWZ_n couplings must be judiously modified to cancel both the $\sim s^2$ and $\sim s$ terms. To explore how well this cancellation occurs one can ask at what value of $\sqrt{s}$ PU is violated, *e.g.*, 1.8 TeV in the SM with no Higgs, but which is essentially infinite in the case of the SM with a light Higgs. Clearly, the larger the value of $\sqrt{s}$ we obtain the better we have done at cancelling all of the dangerous terms. Fig. 3 shows some sample results for PU violation in the Higgsless case. Here we see that variations in the brane terms can lead to substantial alterations in the scale at which PU violation occurs, for some values of the parameters by up to a factor of 4 in comparison to the SM with no Higgs. In the most 'successful'cases the brane term forces the lightest neutral KK to couple to isospin thus enhancing its couplings to WW. Such types of couplings are probably necessary in any realistic model in order to obtain PU. We have not found, however, any pa-

rameter space regions where the PU violation scale gets very large, *e.g.*, 100 TeV. Some such regions may exist but they have yet to be discovered.

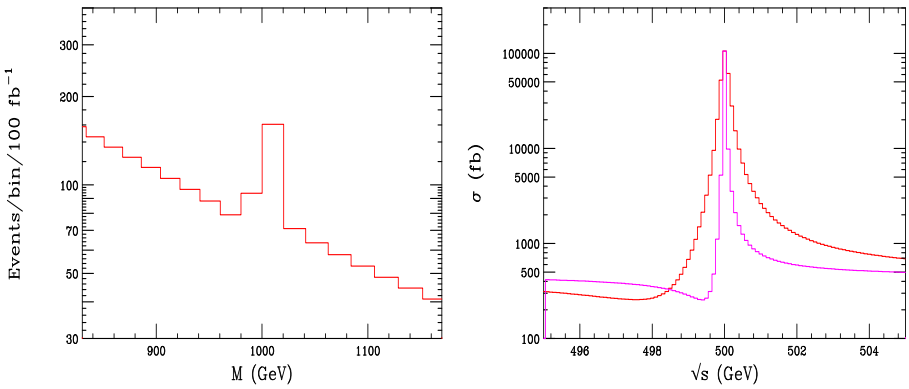

Figure 4: (Left) Drell-Yan cross section for a 1 TeV neutral KK coupling proportional to isospin with 1/20 SM strength at the LHC smeared by the electron pair ATLAS detector resolution. (Right) The corresponding KK unsmeared peaks at the LC for both 1/10 and 1/20 SM couplings. Smearing is important in both cases due to the small width to mass ratio of the KK excitation.

As can be seen from the discussion and examples above it is very difficult for Higgsless models to simultaneously satisfy all of the required constraints and thus it is not trivial to fully imagine what a completely realistic model, if it exists, will look like. However, it is clear that the existence of light KK excitations coupling to isospin will most likely be a necessary ingredient if we want to obtain PU. In addition, such states must have reduced couplings to the SM fermions on the Planck brane in order to avoid present search constraints. Thus one should look for light KK's at future colliders which are somewhat narrow and live in the mass range of 400-1000 GeV. This is an ideal match for both LHC and LC search capabilities as can be seen from Fig. 4. Since the width to mass ratios of these KK states are expected to be small, *e.g.*, $\Gamma/M \sim 10^{-4} - 10^{-3}$, detector smearing issues become of significance at the LHC as do the corresponding issues of beam energy spread at the LC [2]. It is clear from these figures however that if our qualitative understanding of the nature of a 'full' theory is correct we can conclude that such KK states will be observable at both colliders. This may be necessary as it will be the role of the LC to identify the resonance as a KK state arising from a Higgsless model once it is discovered at the LHC.

In summary, we have explored the constraints imposed on the construction

of a successful model of Higgsless EWSB and the possible collider signatures for such a scenario. While such a theory does not yet exist, the challenging search continues.

References

1. For details of this analysis and original references, see H. Davoudiasl, J.L. Hewett, B. Lillie and T.G. Rizzo, hep-ph/0312193 and 0403300.
2. See A. Freitas, these proceedings.