Collider Phenomenology of Higgs Bosons in Left-Right Symmetric Randall-Sundrum Models

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We study the corrections to Higgs physics in a model of a single warped extra dimension with all fields except the Higgs in the bulk, and a gauge symmetry extended to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. We find that generically the Higgs coupling to electroweak gauge boson pairs is suppressed, the coupling to gluons is enhanced, and the coupling to photons is often suppressed, but can be enhanced.

1. RANDALL-SUNDRUM IN THE BULK

In this talk we discuss the physics of the Higgs sector in the context of a proposal for physics beyond the Standard Model (SM), describing the work in [1]. One of the most promising solutions to the hierarchy problem is the Randall-Sundrum (RS) model [2]. In this model there is a single extra dimension compactified on S^1/Z_2 with the non-factorizable metric of AdS_5

$$ds^2 = \left(\frac{R}{z}\right)^2 (dx^2 - dz^2). \tag{1}$$

Here z is the extra-dimensional coordinate, and R is the inverse of the AdS curvature, k. Two branes define the boundaries of the extra dimension. One, at $z = R$, is called the UV, or Planck, brane. The other, at $z = R'$, is the IR, or TeV, brane. Picking $R' = (M_{\text{Planck}}/M_{\text{electroweak}})R$, which is natural in realistic stabilization mechanisms, solves the hierarchy problem.

In the original RS model the SM was confined to the IR brane, and only gravity propagated in the bulk. It has since been realized that both gauge and fermion fields can live in the bulk in a realistic model [4]. These models are realistic, but the parameter space can be strongly reduced by precision electroweak constraints. Much of this problem can be traced to the fact that the massive gauge fields receive a contribution to their mass from the bulk geometry which does not respect the custodial $SU(2)_c$. This can be fixed by expanding the gauge group to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. This dramatically improves the electroweak fit [5]. The breaking of this extended electroweak symmetry proceeds in two stages: on the UV brane $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$; on the IR brane $SU(2)_L \times SU(2)_R \to SU(2)_D$, where $SU(2)_D$ is the diagonal of the $SU(2)$ groups. This paper investigates the properties of the Higgs sector that accomplishes this breaking.

We now ask what drives the breaking on each brane. On the planck brane all degrees of freedom will have Planck scale masses, so we can ignore them. We can then implement the breaking with boundary conditions to good approximation. This leads to the boundary conditions at $z = R$

$$\begin{aligned} \partial_z \left(\frac{\kappa}{\lambda} A_R - A_B\right) &= 0,\ \partial_z A_L = 0, \\ A_B - \frac{\kappa}{\lambda} A_R^3 &= 0,\ A_R^{\pm} = 0. \end{aligned} \tag{2}$$

Here κ and λ are ratios of 5D gauge couplings: $\kappa = g_{5R}/g_{5L}$, and $\lambda = g_{5B}/g_{5L}$.

On the TeV brane, the masses will be TeV scale, so we should look at the Higgs sector in detail. The simplest structure that will create the breaking pattern is a real Higgs that is a bidoublet under $SU(2)_L \times SU(2)_R$. This leads to the boundary conditions at $z = R'$

$$\partial_z (A_L + \kappa A_R) \ = \ 0, \qquad \partial_z A_B = 0,$$

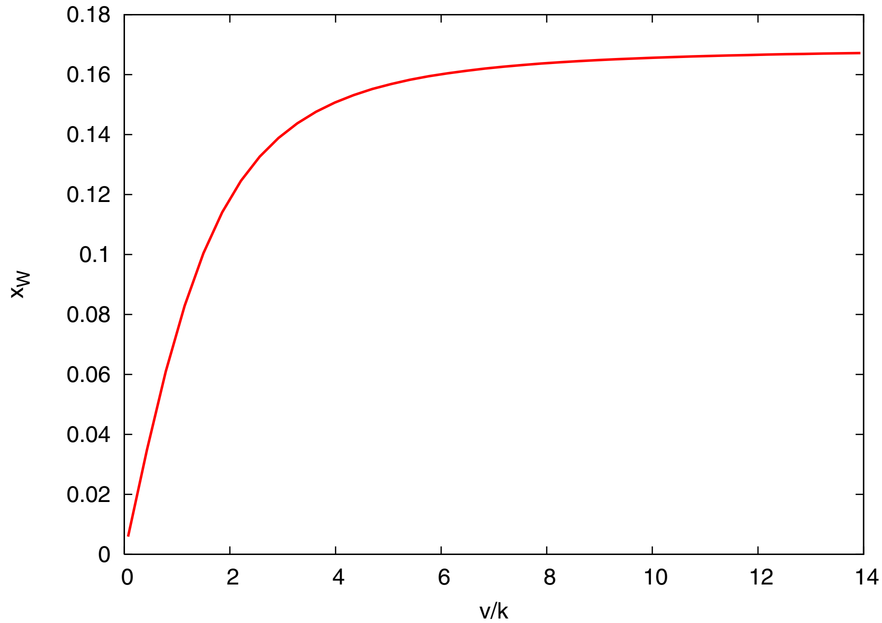

Figure 1: Behavior of the first charged boson mass (corresponding to the observed W) as a function of v/k at fixed k. The linear behavior at small v/k corresponds to the ordinary Higgsed model limit, and the flat behavior as $v/k \to \infty$ to the Higgsless limit.

$$\partial_z(\kappa A_L - A_R) \;=\; -\frac{g_{5L}^2 v^2}{4}(\kappa A_L - A_R). \tag{3}$$

Note that in the $v/k \to \infty$ limit we obtain the usual Higgsless boundary conditions, and this model reduces to the Higgsless model in [6]. We will use this parameter, v/k to interpolate between the SM limit ($v/k \to 0$), and the Higgsless limit.

To write down the effective 4D theory, we expand the 5D fields into Kaluza Klein (KK) fields,

$$A(x,z) = \sum_n \zeta_A^{(n)}(z) A^{(n)}(x) \tag{4}$$

We can now obtain the gauge boson wavefunctions by solving the equation of motion subject to the boundary conditions (2) and (3). This produces a spectrum of eigenvalues corresponding to the excitations of the gauge fields. The lowest masses in each of the charged and neutral sectors will correspond to the W and Z bosons. The neutral sector also contains a zero mode, corresponding to the photon. Fig 1 shows the eigenvalue for the W as a function of the parameter v/k.

2. HIGGS PROPERTIES

One interesting feature of this model is that the W and Z wavefunctions are suppressed near the IR brane, as can be seen by inspecting the boundary conditions. This suppression increases for increasing v/k. This means that the coupling of massive gauge bosons to the Higgs will generically be suppressed. Fig. 1 shows the coupling of the W to the Higgs. For values of v/k near unity the LEP bounds on the Higgs mass can be dramatically reduced. (For larger values of v/k the model is effectively Higgsless.)

The fermion sector of this model is more complicated. Again, the Higgs vev induces mixed boundary conditions that link left and right handed fields to give the fermions masses. However, there are two new degrees of freedom. First, since 5D fermions are achiral, ther can always be a mass term in the bulk $m\bar{\Psi}\Psi$. The main effect of this term is to shift the location of the fermion zero mode in the bulk. By changing this parameter we can cause the zero mode

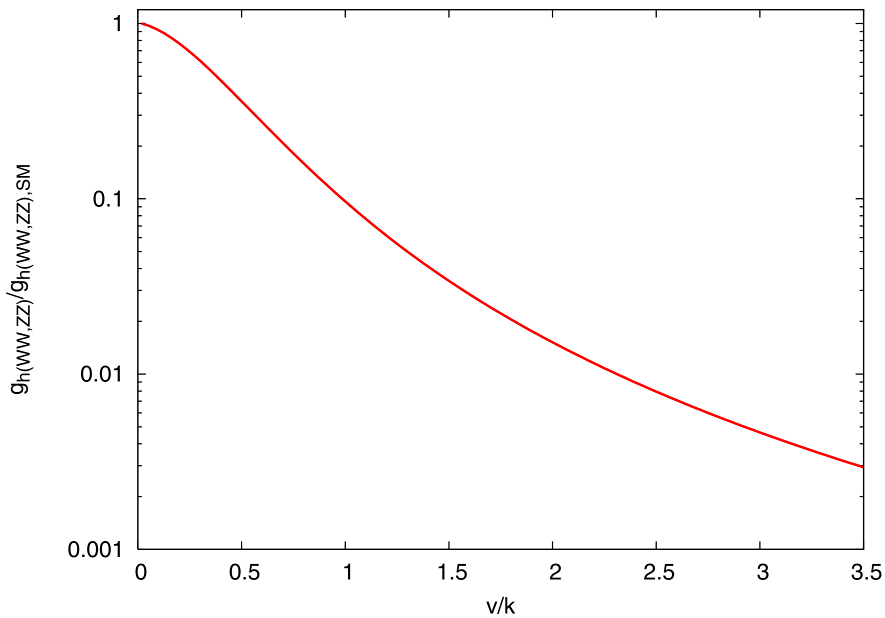

Figure 2: Coupling of the Higgs to vector boson pairs compared to the SM value as a function of v/k. Again, the W and Z coupling strengths are nearly identical due to the custodial symmetry.

to be localized either near the UV or IR brane, and also can change the degree of this localization. This allows us to control the overlap of the zero mode with the IR brane, and consequently the strength with which the fermion interacts with the Higgs. In this way the hierarchy of fermion masses can be generated by order one changes in the 5D masses. The second complication arises from the $SU(2)_R$ symmetry which enforces that, for example, $m_t = m_b$ if unbroken. This mass relation can be modified by mixing with new fermions localized to the Planck brane, where the $SU(2)_R$ is broken. For full details, see [1, 7].

Note that there are tree-level corrections to precision electroweak observables, coming largely from the KK excitations of the gauge bosons. Unfortunately, the magnitude of these corrections is highly sensitive to the configuration of the fermion sector. For the specific configuration studied in [1] we find the constraint $v/k \leq 1/4$. There are, however, special points in the fermion parameter space where the constraint becomes trivial, so a wide range of v/k should be considered.

The final interesting shift in Higgs properties is in the couplings to massless gauge bosons, *i.e.* gluons and photons. The coupling of the Higgs to gluon pairs is induced through top loops. However, in this model the KK excitations also couple to the Higgs. Furthermore, note that we have arranged small 4D Yukawa couplings for the other fermions by small wavefunction overlaps with the would-be zero modes. The 5D Yukawa couplings are all order 1, and the excited states have *no* wavefunction suppression. Hence there are large contributions to the Higgs-glue-glue coupling from the KK excitations of *all* colored fermions. This leads to an enhancement in that coupling, as seen in Fig. 2. There are similar corrections to the Higgs-gamma-gamma coupling. The situation there is more complicated, however, since there are also contributions from W boson loops, which are dominant in the SM, and the Higgs coupling to Ws is suppressed.

We can now look at the behavior of the Higgs branching ratios, as shown in Fig. 2. Note in particular the dominance of $h \to b\bar{b}$ over a wide range, and the late onset of $h \to (WW, ZZ)$. This is driven by the $SU(2)_R$ symmetry, which gives a large enhancement of the b-quark Yukawa, and the suppression of the gauge boson couplings. Note also the reduction in the $h \to \gamma\gamma$ mode. This will make discovery at the LHC difficult. The suppression of the coupling to gauge bosons also means that production at the ILC will be reduced, making this Higgs a particularly difficult one to find. However, it will be essential to measure the Higgs couplings with precision to identify a warped extra dimension as the correct theory of new physics, if indeed this is what is realized in nature.

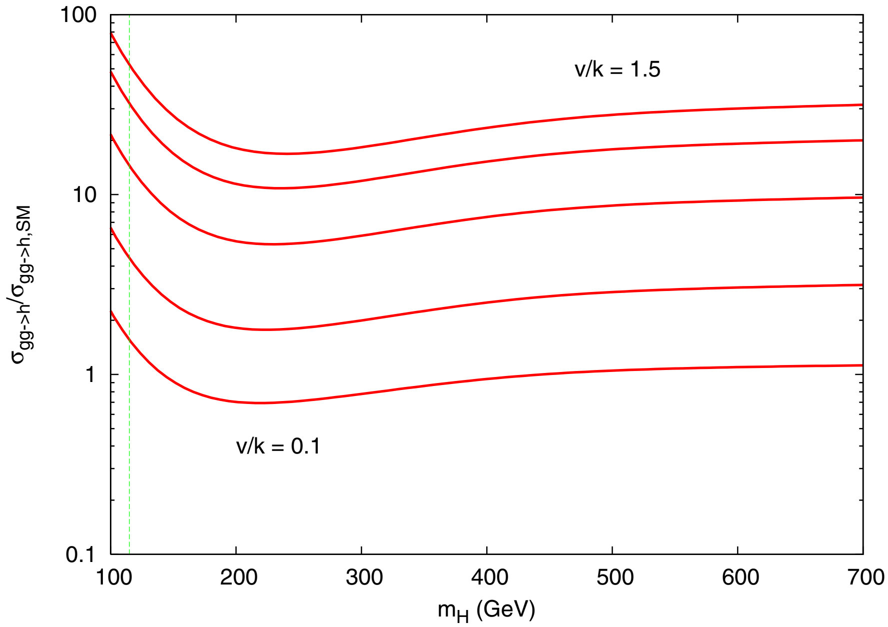

Figure 3: Ratio (at lowest order) of the production cross section for $gg \to h$ compared with the value in the SM. The different curves correspond to the values of v/k from top to bottom of (1.5, 1.1, 0.8, 0.4, 0.1).

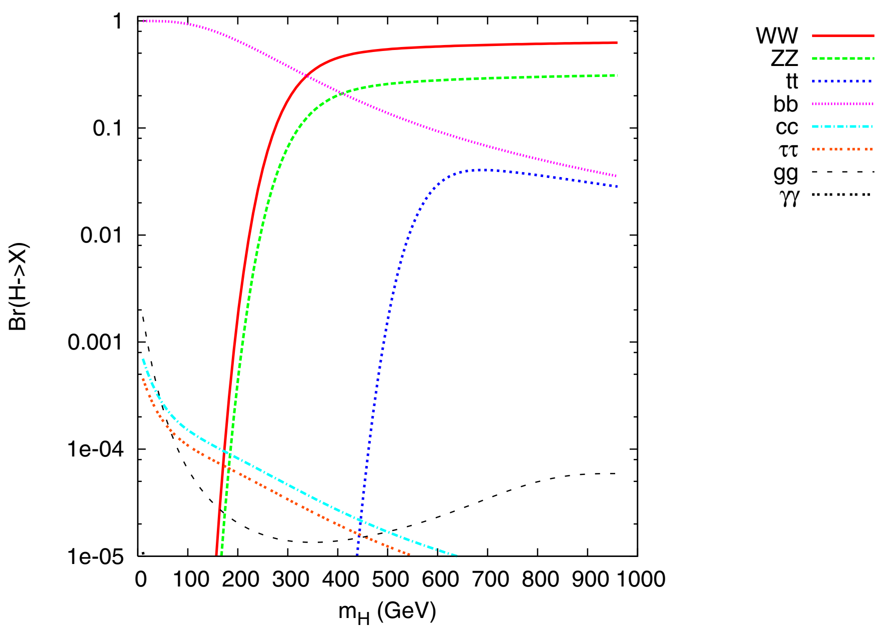

Figure 4: Branching ratios for Higgs decay into various channels as a function of the Higgs mass at fixed $v/k = 1/10$.

Acknowledgments

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