Radion Mixing Effects on the Properties of the Standard Model Higgs Boson

J.L.Hewett and T.G. Rizzo
*SLAC**

We examine how mixing between the Standard Model(SM) Higgs boson, h, and the radion of the Randall-Sundrum model modifies the expected properties of the Higgs boson. In particular we demonstrate that the total and partial decay widths of the Higgs, as well as the $h \to gg$ branching fraction, can be substantially altered from their SM expectations, while the remaining branching fractions are modified less than $\lesssim 5\%$ for most of the parameter region.

The Randall-Sundrum(RS) model[1] offers a potential solution to the hierarchy problem that can be tested at present and future accelerators[2]. In this model the SM fields lie on one of two branes that are embedded in 5-dimensional AdS space described by the metric $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$, where k is the 5-d curvature parameter of order the Planck scale. To solve the hierarchy problem the separation between the two branes, r_c, must have a value of $kr_c \sim 11-12$. That this quantity can be stabilized and made natural has been demonstrated by a number of authors[3] and leads directly to the existence of a radion(r), which corresponds to a quantum excitation of the brane separation. It can be shown that the radion couples to the trace of the stress-energy tensor with a strength Λ of order the TeV scale, *i.e.*, $\mathcal{L}_{eff} = -r\, T^\mu_\mu/\Lambda$. (Note that $\Lambda = \sqrt{3}\Lambda_\pi$ in the notation of Ref.[2].) This leads to gauge and matter couplings that are qualitatively similar to those of the SM Higgs boson. The radion mass (m_r) is expected to be significantly below the scale Λ implying that the radion may be the lightest new field predicted by the RS model. One may expect on general grounds that this mass should lie in the range of a few $\times 10$ GeV $\leq m_r \leq \Lambda$. The phenomenology of the RS radion has been examined by a number of authors[4] and in particular has been reviewed for these proceedings by Kribs[5].

On general grounds of covariance, the radion may mix with the SM Higgs field on the TeV brane through an interaction term of the form

$$S_{rH} = -\xi \int d^4x \sqrt{-g_w} R^{(4)}[g_w] H^\dagger H\,, \qquad (1)$$

where H is the Higgs doublet field, $R^{(4)}[g_w]$ is the Ricci scalar constructed out of the induced metric g_w on the SM brane, and ξ is a mixing parameter assumed to be of order unity and with unknown sign. The above action induces kinetic mixing between the 'weak eigenstate' r_0 and h_0 fields which can be removed through a set of field redefinitions and rotations. Clearly, since the radion and Higgs boson couplings to other SM fields differ this mixing will induce modifications in the usual SM expectations for the Higgs decay widths. To make unique predictions in this scenario we need to specify four parameters: the masses of the *physical* Higgs and radion fields, $m_{h,r}$, the mixing parameter ξ and the ratio v/Λ, where v is the vacuum expectation value of the SM Higgs $\simeq 246$ GeV. Clearly the ratio v/Λ cannot be too large as Λ_π is already bounded from below by collider and electroweak precision data[2]; for definiteness we will take $v/\Lambda \leq 0.2$ and $-1 \leq \xi \leq 1$ in what follows although larger absolute values of ξ have been entertained in the literature. The values of the two physical masses themselves are not arbitrary. When we require that the weak basis mass-squared parameters of the radion and Higgs fields be real, as is required by hermiticity, we obtain an additional constraint on the ratio of the physical radion and Higgs masses which only depends on the product $|\xi|\frac{v}{\Lambda}$. Explicitly one finds that either $\frac{m_r^2}{m_h^2} \geq 1+2\sin^2\rho+2|\sin\rho|\sqrt{1+\sin^2\rho}$ or $\frac{m_r^2}{m_h^2} \leq 1+2\sin^2\rho-2|\sin\rho|\sqrt{1+\sin^2\rho}$ where $\rho = \tan^{-1}(6\xi\frac{v}{\Lambda})$. This disfavors the radion having a mass too close to that of the Higgs when there is significant mixing; the resulting excluded

*hewett@slac.stanford.edu

region is shown in Fig. 1. These constraints are somewhat restrictive; if we take $m_h = 115$ GeV and $\xi\frac{v}{\Lambda} = 0.1(0.2)$ we find that either $m_r > 189(234)$ GeV or $m_r < 70(56)$ GeV. This lower mass range may be disfavored by direct searches.

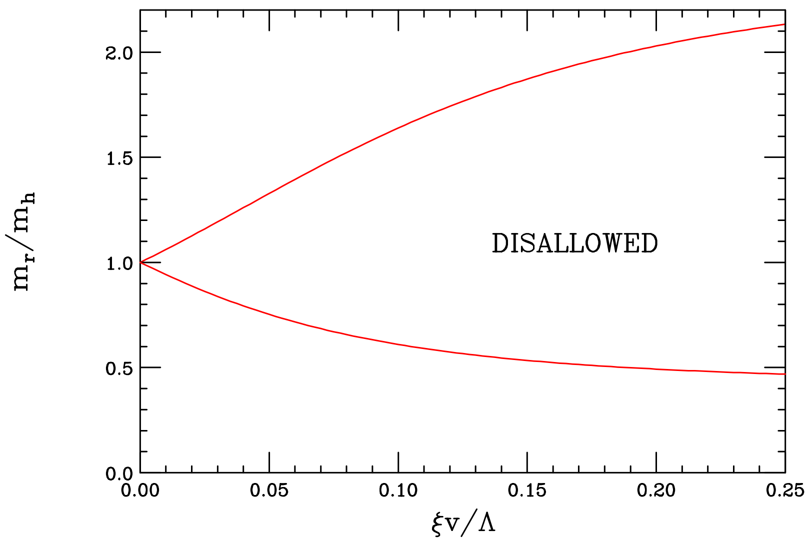

Figure 1: Constraint on the ratio of the mass of the radion to that of the Higgs boson as a function of the product $\xi v/\Lambda$ as described in the text. The disallowed region lies between the curves.

Following the notation of Giudice *et al.*[4], the coupling of the physical Higgs to the SM fermions and massive gauge bosons $V = W, Z$ is now given by

$$\mathcal{L} = \frac{-1}{v}(m_f \bar{f} f - m_V^2 V_\mu V^\mu)[\cos\rho\cos\theta + \frac{v}{\Lambda}(\sin\theta - \sin\rho\cos\theta)]h\,, \tag{2}$$

where the angle ρ is given above and θ can be calculated in terms of the parameters ξ and v/Λ and the physical Higgs and radion masses. Denoting the combinations $\alpha = \cos\rho\cos\theta$ and $\beta = \sin\theta - \sin\rho\cos\theta$, the corresponding Higgs coupling to gluons can be written as $c_g \frac{\alpha_s}{8\pi} G_{\mu\nu}G^{\mu\nu}h$ with $c_g = \frac{-1}{2v}[(\alpha + \frac{v}{\Lambda}\beta)F_g - 2b_3\beta\frac{v}{\Lambda}]$ where $b_3 = 7$ is the $SU(3)$ β-function and F_g is a well-known kinematic function of the ratio of masses of the top quark to the physical Higgs. Similarly the physical Higgs couplings to two photons is now given by $c_\gamma \frac{\alpha_{em}}{8\pi} F_{\mu\nu}F^{\mu\nu}h$ where $c_\gamma = \frac{1}{v}[(b_2 + b_Y)\beta\frac{v}{\Lambda} - (\alpha + \frac{v}{\Lambda}\beta)F_\gamma]$, where $b_2 = 19/6$ and $b_Y = -41/6$ are the $SU(2) \times U(1)$ β-functions and F_γ is another well-known kinematic function of the ratios of the W and top masses to the physical Higgs mass. (Note that in the simultaneous limits $\alpha \to 1$, $\beta \to 0$ we recover the usual SM results.) From these expressions we can now compute the change of the various decay widths and branching fractions of the SM Higgs due to mixing with the radion.

Fig. 2 shows the ratio of the various Higgs widths in comparison to their SM expectations as functions of the parameter ξ assuming that $m_h = 125$ GeV with different values of m_r and $\frac{v}{\Lambda}$. We see several features right away: (i) the shifts in the widths to $\bar{f}f/VV$ and $\gamma\gamma$ final states are very similar; this is due to the relatively large magnitude of F_γ while the combination $b_2 + b_Y$ is rather small. (ii) On the otherhand the shift for the gg final state is quite different since F_g is smaller than F_γ and b_3 is quite large. (iii) For relatively light radions with a low value of Λ the width into the gg final state can come close to vanishing due to a strong destructive interference between the two contributions to the amplitude for values of ξ near -1. (iv) Increasing the value of m_r has less of an effect on the width shifts than does a decrease in the ratio $\frac{v}{\Lambda}$.

The deviation from the SM expectations for the various branching fractions, as well as the total width, of the Higgs are displayed in Fig. 3 as a function of the mixing parameter ξ. We see that the gluon branching fraction and the total width may be drastically different than that of the SM. The former will affect the Higgs production cross section at the LHC. However, the $\gamma\gamma$, $f\bar{f}$, and VV, where $V = W, Z$ branching fractions receive small corrections to their SM values, of order $\lesssim 5\%$ for most of the parameter region. Observation of these shifts will require the accurate determination of the Higgs branching fractions available at an e^+e^- Linear Collider.

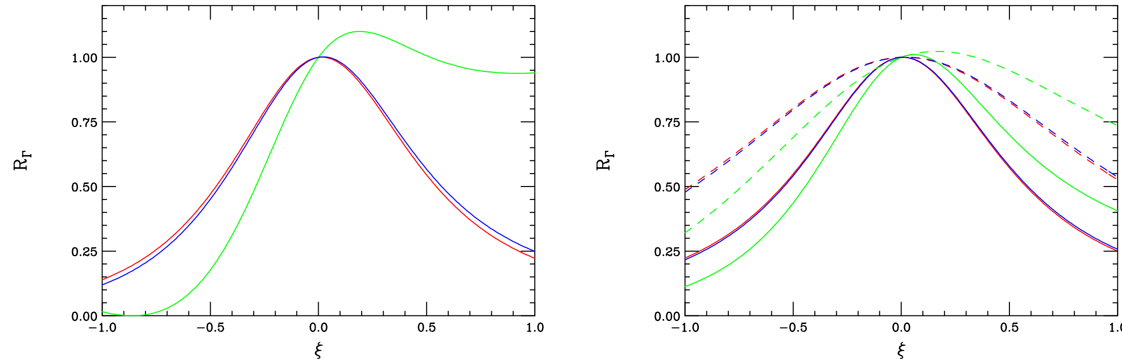

Figure 2: Ratio of Higgs widths to their SM values, R_Γ, as a function of ξ assuming a physical Higgs mass of 125 GeV: red for fermion pairs or massive gauge boson pairs, green for gluons and blue for photons. In the left panel we assume $m_r = 300$ GeV and $v/\Lambda = 0.2$. In the right panel the solid(dashed) curves are for $m_r = 500(300)$ GeV and $v/\Lambda = 0.2(0.1)$.

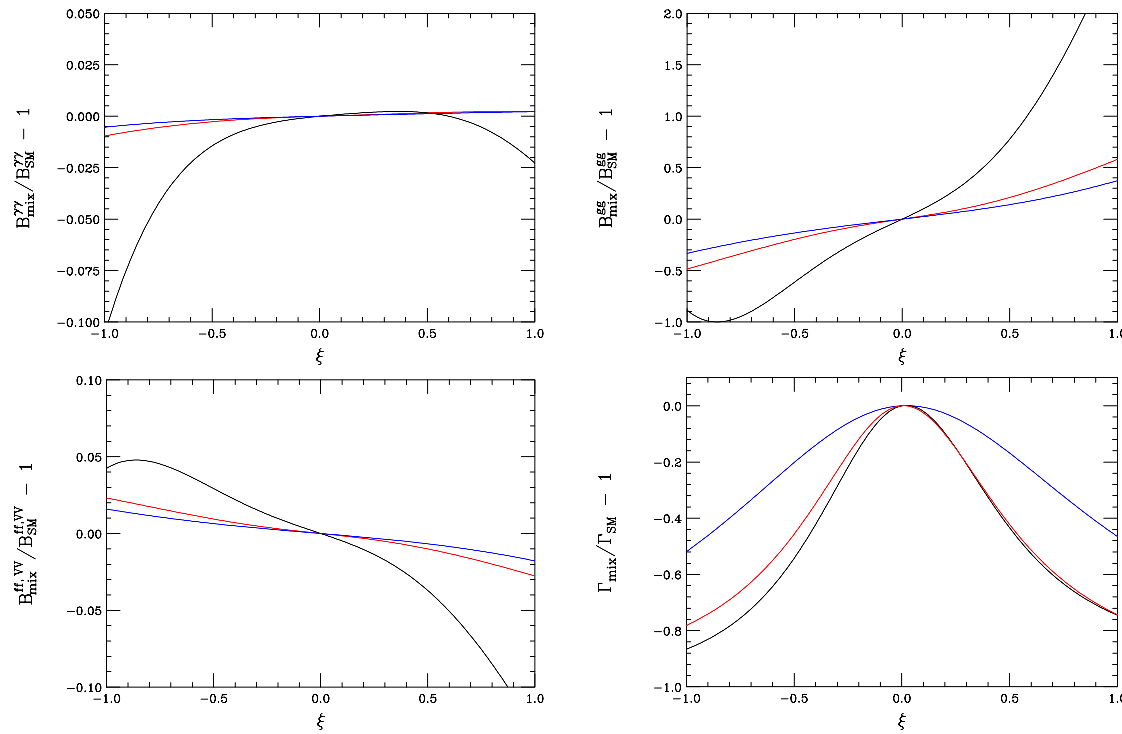

Figure 3: The deviation from the SM expectations for the Higgs branching fraction into $\gamma\gamma$, gg, $f\bar{f}$, and VV final states as labeled, as well as for the total width. The black, red, and blue curves correspond to the parameter choices $m_r = 300, 500, 300$ GeV with $v/\xi = 0.2, 0.2, 0.1$, respectively.

In summary, we see that Higgs-radion mixing, which is present in some extra dimensional scenarios, can have a substantial effect on the properties of the Higgs boson. These modifications affect the widths and branching fractions of Higgs decay into various final states, which in turn can alter the Higgs production cross section at the LHC and may require the precision of a Linear Collider to detect.

References

[1] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999).

[2] For an overview of RS phenomenology, see H. Davoudiasl, J.L. Hewett and T.G. Rizzo, Phys. Rev. Lett. **84**, 2080 (2000); Phys. Lett. **B493**, 135 (2000); and Phys. Rev. **D63**, 075004 (2001).
[3] W.D. Goldberger and M. Wise, Phys. Rev. Lett. **83**, 4922 (1999) and Phys. Lett. **475**, 275 (2000); C. Csaki, M. Graesser, L. Randall and J. Terning, Phys. Rev. **D62**, 045015 (2000); C. Csaki, M. Graesser, and G.D. Kribs, Phys. Rev. **D63**, 065002 (2001); C. Charmousis, R. Gregory and V.A. Rubakov, Phys. Rev. **D62**, 067505 (;)T. Tanaka and X. Montes, Nucl. Phys. **B582**, 259 (2000).
[4] G.F. Giudice, R. Rattazzi and Wells, Nucl. Phys. **B595**, 250 (2001); U. Mahanta and A. Datta, Phys. Lett. **B483**, 196 (2000); T. Han, G.D. Kribs and B. McElrath, Phys. Rev. **D64**, 076003 (2001); M. Chaichian, A. Datta, K. Huitu and Z. Yu, hep-ph/0110035; M. Chaichian, K. Huitu, A. Kobakhidze and Z.-H. Yu, Phys. Lett. **B515**, 65 (2001); S.B. Bae, P. Ko, H.S. Lee and J. Lee, Phys. Lett. **B487**, 299 (2000); S.B. Bae and H.S Lee, hep-ph/0011275; S.C. Park, H.S. Song and J. Song, hep-ph/0103308; S.R. Choudhury, A.S. Cornell and G.C. Joshi, hep-ph/0012043; K. Cheung, Phys. Rev. **D63**, 056007 (2001).
[5] G.D. Kribs, hep-ph/0110242 and these proceedings.