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# Phenomenology of radions

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**Abstract.** In this paper I will discuss the phenomenology of radion of the Randall–Sundrum type models. I will consider the radion couplings and its production and decay, in the same time taking into account the mixing of radion with Higgs.

**Keywords.** Radion; extra dimensions.

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## 1. Introduction

The hierarchy problem is a strong motivation for the beyond the standard model (BSM) physics. Several proposals have been made in order to improve the naturalness of the standard model (SM) describing the basic structure of matter. The obvious first trial was the composite models, in which a new level of matter is introduced beyond the standard model particles. Unfortunately it is not easy to construct viable models along this line. Supersymmetric models on the other hand seem to be flexible enough to be consistent with experiments and at the same time to provide us with an interesting possibility to exactly cancel the problematic terms in the SM. It has turned out that, if physical, supersymmetry is badly broken. The breaking of supersymmetry has been parameterized by the so-called soft breaking terms, which will not bring back the unnaturalness after the symmetry is broken. However, these new terms add arbitrariness to the theory.

Recently new ideas of getting rid of the hierarchy problem with extra dimensions has appeared [1,2]. In more than the known four dimensions, one could bring the fundamental mass scale down to the TeV scale, thus removing the hierarchy problem. In the original works the extra dimension was considered large [1]. In that case the Planck mass in the model is $M_{\rm Planck}^2 = M^{n+2}V_n$ and there is a large new hierarchy between the five-dimensional Planck mass and the size of the extra dimensions. The big difference to the SM is the graviton Kaluza–Klein tower at $\mathcal{O}(1\ \text{TeV})$, causing possibly detectable effects, see e.g. [3]. In this situation the number of extra dimensions can vary, and any number of dimensions larger than one is acceptable from the experimental point of view.

Another possibility to get rid of the hierarchy problem is via an exponential 'warp' factor, which brings all the Planck level masses down to the TeV-scale masses in the visible sector without introducing new type of fine-tuning. In the Randall-Sundrum (RS) model [2] $M_{\rm Planck}^2 = (M^3/k)(1-{\rm e}^{-2kr_{\rm c}\pi})$, where $k \sim M$ and $r_{\rm c}$ is the compactification radius.

The interesting point in both of the above mentioned extra dimensional models is that if this kind of model is realized in nature, there is a possiblity to probe the structure of space-time already at TeV scale colliders.

The RS model has five dimensions. The extra dimension will be compactified e.g. on an orbifold $S_1/Z_2$ with two branes at fixed points. The metric is given by [2]

$$\mathrm{d}s^2 = \mathrm{e}^{-2kr_\mathrm{c}|y|}\eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu - r_\mathrm{c}^2\mathrm{d}y^2, \tag{1}$$

where the coordinate of the extra dimension $y \in [-\pi,\pi]$. Two kinds of massless fields are allowed: graviton due to the fluctuations around the metric, and radion due to the fluctuations in the distance between the branes. Since $r_\mathrm{c}$ is undetermined, the extra dimension must necessarily be stabilized. There are different ways to stabilize the extra dimension. In the method of Goldberger and Wise [4], one has scalar fields $S(x,y)$ in the bulk potential with vacuum expactation value (VEV), which depends on the extra dimension $\langle S(x,y)\rangle = \tilde{S}(y)$. Then one gets an effective potential for the radion $\phi$ by integrating over $y$.

Another possibility is to supersymmetrize the scenario [5]. Then the stabilization can be done by super Yang–Mills sectors in the bulk and on the hidden brane. Interestingly one can get a viable version of the anomaly mediated symmetry breaking in this case [6].

The mass of the radion depends on the stabilization method, but generally it can be lighter than the Kaluza–Klein modes of graviton, in which case the radion would be the first particle indicating extra dimensions.

## 2. Radion couplings

Radion couples to the trace of the stress–energy tensor [7,8]. From the phenomenological point of view, the crucial feature of the coupling is that it is suppressed only by the VEV of the radion,

$$\mathscr{L}_\mathrm{int} = \frac{\phi}{\Lambda_\phi}\, T_\mu^\mu(\mathrm{SM}), \tag{2}$$

where $T_\mu^\mu(\mathrm{SM}) = \sum_f m_f \bar{f} f - 2m_W^2 W_\mu^+ W^{-\mu} - m_Z^2 Z_\mu Z^\mu + (2m_h^2 h^2 - \partial_\mu h \partial^\mu h) + \cdots$. Due to the trace anomaly, there are in addition terms, which allow direct coupling of radion to the gauge bosons,

$$T_\mu^\mu(\mathrm{SM})^\mathrm{anom} = \sum_a \frac{\beta_a(g_a)}{2g_a} F_{\mu\nu}^a F^{a\mu\nu}. \tag{3}$$

These are important especially for gluon coupling to radions.

## 3. Radion and Higgs mixing

Generally speaking, radion and Higgs mix with each other, since all symmetries of the model allow in the action the mixing term [9,10]:

$$S = -\xi \int \mathrm{d}^4 x \sqrt{-g_{\text{vis}}} R(g_{\text{vis}}) H^\dagger H. \tag{4}$$

After the shift $\phi \to \phi + \Lambda_\phi$, one finds for the radion-Higgs mixing Lagrangian:

$$\mathscr{L} = -\frac{1}{2}\phi[(1-6\xi\gamma^2)\Box + m_\phi^2]\phi - \frac{1}{2}h(\Box + m_h^2)h - \frac{6\xi v}{\Lambda_\phi}\phi\Box h, \tag{5}$$

where $m_\phi$, $m_h$ =radion and Higgs mass parameters, and $\gamma = v/\Lambda_\phi$.

Diagonalization of the mixing equations gives [10,11]

$$\phi = a\phi' + bh', \quad h = c\phi' + dh', \tag{6}$$

where

$$a = \cos\theta/Z, \quad b = -\sin\theta/Z,$$
$$c = \sin\theta - 6\xi\gamma/Z\cos\theta, \quad d = \cos\theta + 6\xi\gamma/Z\sin\theta,$$
$$Z^2 = 1 - 6\xi\gamma^2(1+6\xi), \quad \tan 2\theta = 12\xi\gamma Z \frac{m_h^2}{m_h^2(Z^2 - 36\xi^2\gamma^2) - m_\phi^2}.$$

For the Higgs mixing parameter, $\xi$, one finds $-[(1+\sqrt{1+4/\gamma^2})/12] \le \xi \le [(\sqrt{1+4/\gamma^2}-1)/12]$. Thus for $\Lambda_\phi = 1$ TeV, $-0.75 \lesssim \xi \lesssim 0.56$.

The mass eigenstates are the radion $\phi'$ and Higgs $h'$ with masses

$$m_{\phi'}^2 = c^2 m_h^2 + a^2 m_\phi^2, \quad m_{h'}^2 = d^2 m_h^2 + b^2 m_\phi^2. \tag{7}$$

Note that the mixing matrix of radion and Higgs is not unitary.

The interaction Lagrangian of $\phi'$ and $h'$ with fermions and massive gauge bosons is given by

$$\mathscr{L} = -\frac{1}{\Lambda_\phi}(m_{ij}\bar{\psi}_i\psi_j - M_V^2 V_{A\mu}V_A^\mu)\left[a_{34}\frac{\Lambda_\phi}{v}h' + a_{12}\phi'\right], \tag{8}$$

where $a_{12} = a + c/\gamma$ and $a_{34} = d + b\gamma$. Here $a_{12}$ and $a_{34}$ give the strength of the interaction compared to the case with no mixing. For light radions, $a_{12}$ is larger than one for all $\xi > 0$, while for heavy radions, $a_{12}$ first decreases and vanishes at $\xi = 1/6$, but the contribution of $\phi'$ again increases for large $\xi$ [11]. The Higgs interaction suppression factor $a_{34}$ is close to one, except for strong mixing of $\phi'$ and $h'$. Coupling of radion to Higgs changes to

$$\begin{aligned} V_{\phi' h' h'} = \frac{1}{\Lambda_\phi}\big(& 2m_h^2 ad^2 h'^2\phi' - ad^2\phi'\partial_\mu h'\partial^\mu h'(1-6\xi) + 6\xi ad^2(h'\Box h')\phi' \\ & -2bcdh'\partial_\mu\phi'\partial^\mu h'(1-6\xi) + 4m_h^2 bcd\phi' h'^2 \\ & +6bcd\xi h'(\phi'\Box h' + h'\Box\phi')\big) \end{aligned} \tag{9}$$

and the radion and Higgs coupling to $gg$ and $\gamma\gamma$ are given by

$$V_{gg} = \frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{\mu\nu a} \left[ \frac{1}{\Lambda_\phi} \left( ab_3 - \frac{1}{2} a_{12} F_{1/2}(\tau_t) \right) \phi' + \left( \frac{1}{\Lambda_\phi} bb_3 - \frac{1}{2v} a_{34} F_{1/2}(\tau_t) \right) h' \right], \tag{10}$$

and

$$V_{\gamma\gamma} = \frac{\alpha_{EM}}{8\pi} F_{\mu\nu} F^{\mu\nu} \left[ \frac{1}{\Lambda_\phi} \left( a(b_2 + b_Y) - a_{12} \left( F_1(\tau_W) + \frac{4}{3} F_{1/2}(\tau_t) \right) \right) \phi' + \frac{1}{v} \left( \frac{v}{\Lambda_\phi} b(b_2 + b_Y) - a_{34} \left( F_1(\tau_W) + \frac{4}{3} F_{1/2}(\tau_t) \right) \right) h' \right]. \tag{11}$$

## 4. Radion and Higgs decay

Because of the mixing the decay patterns of Higgs and radion will change. For large mixing and heavy $h'$, the decay of Higgs to $WW$ and $ZZ$ will dominate, and for radions heavier than twice the physical Higgs mass, the decay to Higgs and for larger masses to gluons will be dominant. Compared to the unmixed case, the branching ratios of heavy radion are changed. In the unmixed case, also for heavy radion, the dominant decay modes are to the weak gauge bosons, and the branching ratio to gluons is at the percentage level [11,12]. The $h'gg$ coupling has two terms, which may cancel at some $m_{h'}$ value, giving zero width. This will also affect the $h'$ signals [13].

In the unmixed case, the total width of the radion is similar to the width of the Higgs for similar radion and Higgs VEV's. For light and again for heavy radion masses, the radion width is slightly larger because of the anomalous couplings. However, the width decreases as the square of the radion VEV [14]. In the mixed case, the width decreases when $\xi$ increases from zero to $1/6$, and begins to rise again for larger values of $\xi$ [9].

## 5. Radion and Higgs production

The background for radion production in linear colliders is easier to handle than that in hadron colliders. The production cross section for $e^+e^-$ colliders for similar radion and Higgs VEV's is similar, since the anomalous contribution to $WW$ and $ZZ$ couplings is not significant, when also the tree level couplings exist. On the other hand, the anomalous coupling to gauge bosons helps in the production of radions at $\gamma\gamma$ colliders. The phenomenology in these machines has been discussed e.g. in [11,12,14,15].

The production in hadron colliders is discussed in [9,12–16]. The production cross sections of Higgs and radion have been discussed e.g. in [13] in gluon–gluon fusion, multiplied by the branching ratios to $\gamma\gamma$, $ZZ$ and $WW$ decay modes ($ZZ$ and $WW$ cross sections will be further multiplied by the branching ratios $Z \to l^+l^-$ and $W \to l\nu_l$; where $l \equiv e, \mu$). Gluon–gluon fusion is the dominant production process for the Higgs and production cross section is further enhanced by the trace anomaly in radion production. In the case of strong mixing, the effects of $a_{12}$ variation, as well as the dip in $h'gg$ coupling are clearly visible in these considerations [13].

The $\gamma\gamma$ and $ZZ$ event rates at large hadron collider (LHC) have been discussed in [13] as a function of the mixing parameter $\xi$. The $\phi', h' \to WW \to l^+\nu l^-\bar{\nu}$ effective branching ratio is almost an order of magnitude greater than that of $\phi', h' \to ZZ \to l^+l^-l^+l^-$ channel. Therefore, it is evident that the mass reach of the $WW$ channel is better than that of the $ZZ$ channel for a particular value of $\xi$, but the signal is more complicated. Both $\phi'$ and $h'$ event rates significantly increase with the absolute value of the mixing parameter for the $ZZ \to l^+l^-l^+l^-$ channel, and $h'$ rates for the $\gamma\gamma$ channel. The $h'$ event rate is more sensitive to the mixing parameter which is evident from both the channels.

Generally speaking, the role of $\xi$ is crucial in determining the physical masses of the scalars as well as the couplings of them to the SM fields.

## 6. Discussion and conclusions

If the extra dimensions are realized in nature, the radion would be a natural candidate to test the model. The mixing of radions with Higgs bosons may require new search strategy at LHC.

There have been attempts to supersymmetrize the Randall–Sundrum model. Even if both the RS model and the supersymmetric models aim to solve the hierarchy problem, both may be needed. To make contact with a more fundamental theory, the warped scenario may need to be supersymmetrized. On the other hand, supersymmetric models suffer from flavor problem and the so-called $\mu$ problem, which both may be solved in extra dimensional scenarios. In supersymmetrized models one has a new particle, the partner of the radion, called radino [17].

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