Physics of the Radion in the Randall-Sundrum Scenario

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In the Randall-Sundrum solution to the hierarchy problem, the fluctuations of the size of the extra dimension are characterized by a single scalar field, called the radion. The radion is expected to have a mass somewhat lower than the TeV scale with couplings of order 1/TeV to the trace of the energy momentum tensor. In addition, the radion can mix with the Higgs boson. Implications for phenomenology are briefly reviewed.

1. Introduction

Randall and Sundrum (RS) proposed a fascinating solution to the hierarchy problem [1]. The setup involves two 4D surfaces ("branes") bounding a slice of 5D compact AdS space taken to be on an S^1/Z_2 orbifold. Gravity is effectively localized one brane, while the Standard Model (SM) fields are assumed to be localized on the other. The wavefunction overlap of the graviton with the SM brane is exponentially suppressed, causing the masses of all fields localized on the SM brane to be exponentially rescaled. The hierarchy problem can be solved by assuming all fields initially have masses near the 4D Planck scale, and arranging that the exponential suppression rescales the Planck mass to a TeV on the SM brane. This requires stabilizing the size of the extra dimension to be about thirty-five times larger than the AdS radius. Goldberger and Wise [2] proposed adding a massive bulk scalar field with suitable brane potentials causing it to acquire a vev with a nontrivial x_5-dependent profile. The desired exponential suppression could be obtained without any large fine-tuning of parameters. Fluctuations about the stabilized RS model include both tensor and scalar modes. In this brief review, the fluctuations of the size of the extra dimension, characterized by the scalar (g_{55}) component of the metric otherwise known as the radion, are discussed.

2. Radion mass

Given a stabilizing mechanism, the radion mass can in principle be calculated. In the Randall-Sundrum model with a bulk scalar field, this was estimated in Refs. [2, 3, 4]. A self-consistent calculation requires an ansatz of the scalar fluctuations about the RS background that solve the (linearized) Einstein equations [5], and incorporating the backreaction of the bulk scalar vev into the metric [6]. Treating the backreaction as a perturbation about the RS solution, the mass was found to be [7] (see also [8])

$$m_r \sim (\text{backreaction}) \frac{\Lambda}{35} \tag{1}$$

in terms of the "warped" Planck scale $\Lambda = e^{-kL} M_{\rm Pl} \sim \mathcal{O}(\text{TeV})$. Note that in the limit the backreaction goes to zero, the radion mass vanishes. Thus, the expectation is that the radion is the lightest state in the RS model beyond the SM fields (as compared with the Kaluza-Klein gravitons that have masses of order Λ). The precise mass of the radion is, however, dependent on the details of the stabilization mechanism. For phenomenological purposes, a sensible range for the radion mass is probably $\mathcal{O}(10\text{ GeV}) \lesssim m_r \lesssim \Lambda$, where the lower limit arises from radiative corrections from SM fields, and the upper limit is the cutoff of the 4D effective theory.

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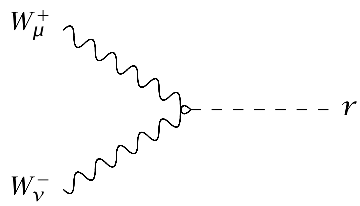
3. Radion couplings

The linear coupling of the canonically normalized radion is [3, 4]

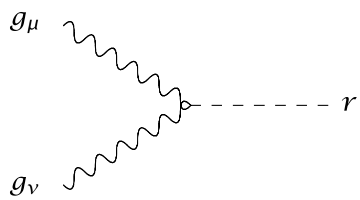
$$-\frac{r(x)}{\sqrt{6}\Lambda} T_{\mu}^{\mathrm{SM}\,\mu} \tag{2}$$

obtained by varying the action with respect to the g_{55} component of the metric. Here $T_{\mu\nu}^{\mathrm{SM}}$ is the energy-momentum tensor of the SM. The key observation is that the coupling is order $1/\Lambda$ (and not $1/M_{\mathrm{Pl}}$) as a result of the exponential rescaling. The radion can therefore be produced and decay on collider time scales. The radion couples to all terms that violate scale invariance, which can be easily read off from Eq. (2). At leading order this includes mass terms in the SM and kinetic terms for the Higgs boson (and Goldstone bosons). This leads to 3-point couplings of the radion such as



$$-i\eta_{\mu\nu}\gamma 2M_W^2/v$$

where I have defined the coupling $\gamma \equiv v/(\sqrt{6}\Lambda)$. Since matter fermion and gauge boson masses arise through the Higgs vev, not surprisingly the radion couplings are rather similar to the Higgs boson. Indeed tree-level couplings of the radion can be obtained by replacing $h(x) \to -\gamma r(x)$ everywhere in the SM. One important difference is that, due to the trace anomaly, there are direct couplings of the radion to massless gauge bosons at one-loop [9, 10]. For example, the radion coupling to two gluons through the trace anomaly is



$$-i[2\,p\cdot q\,\eta_{\mu\nu} - p_\mu q_\nu - q_\mu p_\nu]\gamma b_3 \frac{g_3^2}{32\pi^2 v}$$

where b_3 is the one-loop QCD β-function coefficient.

4. Radion production

The loop-suppressed but β-function enhanced coupling of the radion to gluons provides the dominant production process at hadron colliders (see e.g. [9, 10, 11]). At e^+e^- machines, the dominant production processes are analogous to those of Higgs production, such as $e^+e^- \to Zr$. In fact, the radion production cross section can be functionally related to the Higgs production cross section

$$\sigma(e^+e^- \to Zr) = \gamma^2\sigma(e^+e^- \to Zh; m_h \to m_r)\ . \tag{3}$$

This leads to what are likely the best bounds on the radion mass as function of γ (or, equivalently, the cutoff scale). A theoretical estimate of the bound was given in [7] (see also [12]), suggesting the radion mass is unconstrained for $\gamma \lesssim 0.1$ ($\Lambda = 1$ TeV), but must be $\gtrsim 100$ GeV for $\gamma \sim 1$. In fact, an experimental analysis in the context of a two-Higgs doublet model, replacing $\sin^2(\beta - \alpha)$ with γ^2, suggested this theoretical estimate was reasonable [13].

5. Radion decay

The decay of the radion has been well-studied by e.g. [9, 11]. Due to the trace anomaly coupling to gluons, the dominant decay of the radion for masses between about $12m_b \lesssim m_r \lesssim 2M_W$ is $r \to gg$. For somewhat lower masses, $r \to b\overline{b}$ is important, while for higher masses the decays

$r \to W^+W^-, ZZ, hh$ have the largest branching ratios. This means the search strategy for the radion could be quite different than that for the SM Higgs, particularly for small to intermediate masses.

6. Radion-Higgs mixing

Up to now I have assumed the sole interactions of the radion are given by Eq. (2). There is, however, one important term in the low energy 4D effective theory allowed by all symmetries that mixes the radion with the Higgs [9]

$$S_{mixing} = \xi \int d^4x \sqrt{g_{\rm ind}} R^{(4)}(g_{\rm ind}) H^\dagger H \, , \tag{4}$$

where $R^{(4)}$ is the 4D Ricci scalar constructed out of the induced metric on the SM brane, and ξ is a dimensionless coupling. This leads to kinetic mixing between the radion and Higgs fields. The physical mass eigenstates are thus mixtures of the radion and Higgs; details can be found in [7, 9].

This can wreak havoc on your intuition concerning Higgs and radion fields. Let me provide two examples. Precision electroweak observables receive contributions from both the radion and the Higgs. In the absence of radion-Higgs mixing, the contribution of the radion is always small since it is functionally analogous to the Higgs, but with couplings suppressed by γ. With significant radion-Higgs mixing, the summed contribution of the two physical scalars (formerly the radion and Higgs) can be quite different. In particular, it is possible to satisfy current constraints on the oblique parameters S and T [14] while pushing both the radion and Higgs masses to the several hundred GeV range, provided ξ is moderate and negative [7]. The second example is the partial-wave amplitude for electroweak gauge boson scattering. Again, in the absence of radion-Higgs mixing, the radion contribution is always perturbative up to the 4D cutoff scale Λ. For large radion-Higgs mixing, however, the gauge boson scattering can become strong prior to reaching Λ [15]. Other examples involving mixed scalar production and decay can be found in e.g. [9, 16].

7. Summary

I have sketched the mass, couplings, production, decay, and mixing of the radion in the Randall-Sundrum scenario. The radion is expected to be the lightest state beyond the SM with properties that are similar (but with important differences) to the SM Higgs boson. Furthermore, the radion and the Higgs can mix through an additional allowed operator in the 4D effective theory. If this mixing is significant, the direct and indirect effects of what were the physical radion and Higgs states can be significantly altered.

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