RS at LHC, a birds-eye view for hep-ex
Notes for my Cornell CMS mini-workshop talk

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19 January 2012

1 Introduction

These are notes for my talk at the LEPP workshop on future CMS analysis directions (19–20 Jan 2012); please see the slides for the relevant plots and graphics. They are not intended for general distribution. The goal of this talk is to present the status of 'realistic' Randall-Sundrum models to experimentalists. We will focus on the phenomenology of favored models and highlight differences from what is often referred to as RS1 in the experimental community. I'll try to include some useful references, though these are far from comprehensive.

Remark on conventions: In the heuristic equations in this note we will use conformal coordinates. The original RS1 paper and some fraction of model builders use exponential coordinates. Since this talk is meant to be heuristic rather than technical, we won't go to great length to translate between the two. Roughly, however, the key conversion is that the conformal coordinate z is related to the exponential coordinate y via $z = R \exp ky$ where curvature is $k \sim 1/R$ and the size of the extra dimension is R'. The warp factor between the fundamental and the IR scales is $R/R' \ll 1$.

2 Motivation

We'll skip the usual top-down motivation from the hierarchy problem. One might wonder why extra dimensions (rather than SUSY, etc.) should be plausible at the LHC. Such a scenario seems rather disconnected from what we know about nature—maybe extra dimensions should be left to stringy considerations at the Planck scale. A powerful motivation, however, comes from the AdS/CFT correspondence, which—for our purposes—boils down to the following:

> **Theorist:** I have this great new theory.
> **Experimentalist:** Neat. What does it predict?
> **Theorist:** Well, you have a series of evenly spaced resonances...
> **Experimentalist:** We already discovered that! They're called hadrons.

The point of the story is that extra dimensions predicts Kaluza-Klein excitations of each field. These can be identified with bound states of a strongly coupled theory (e.g. QCD). While 'extra dimensions' may sound exotic, strong coupling is something that we *know* exists in nature. Models of warped extra dimensions give us a handle for the phenomenology of the low energy behavior of models of new strongly coupled physics.

3 Evolution of RS

> The discrepancy between the theorist and experimentalist versions of the RS1 model is perhaps best understood using a science fiction trope. Imagine an alien race that sends scouts millions of light years to Earth to assess whether it can be colonized. The scouts find the planet full of natural resources, devoid of intelligent life up to dolphins and monkeys. They report back to their leaders and soon a fleet travels millions of light years to Earth to set up a colony. Much to their surprise, the planet now has nuclear weapons and the leader of the free world is a trigger-happy Texan. In the same way, model building has progressed since the original RS1 model.

The original Randall–Sundrum 1 (RS1) framework was published in 1999. In most experimental literature, this is the model which is considered when referring to RS1. Over the last decade, however, the model has evolved to address challenges and take advantage of opportunities. The modern, or 'realistic' RS1 scenario that theorists now refer to has rather different signatures.

- **Pre-RS1:** We will not discuss variants with a flat extra dimension. For more information, look up the ADD ('large extra dimension') model or UED (universal extra dimension) models.
- **Original RS1:** `hep-ph/9905221` . SM on the IR brane. The Planck–TeV hierarchy is generated by warping the space between the branes, $M_{\mathbf{Pl}}$ is warped down to TeV at the IR brane. The main signature are graviton KK modes since gravity is the only thing to propagate in the bulk. We will not consider the non-compact RS2 model.
- **RS1 with Bulk Fields:** `hep-ph/9911262` , `hep-ph/9912408` , `hep-ph/0003129` . It was quickly realized that by pulling the Standard Model fields into the extra dimension one could solve problems with electroweak precision observables (specifically the S-parameter) and flavor-changing neutral currents. In order to maintain the solution to the Hierarchy problem, the Higgs remained on the IR brane (or highly peaked toward it). An added benefit of this framework is that one can naturally explain the hierarchy in fermion masses with anarchic Yukawa matrices.
- **Custodial RS1:** `hep-ph/0308036` . Even with bulk fields, the 'realistic' RS1 models suffer from generically large contributions to the T-parameter. One way to solve this is to impose a custodial symmetry on the model. The bulk gauge symmetry is $SU(2)_L \times SU(2)_R \times U(1)_X$, and the model has additional heavy matter and gauge states.
- **Variants and extensions of RS1:** Even with bulk fields and custodial symmetry, the above models still have a 'little hierarchy problem' owing to the discrepancy between the $\mathcal{O}$(1–10 TeV) IR brane scale and the electroweak scale. Ways to avoid this include Higgsless models (`hep-ph/0305237`), the gaugephobic Higgs (`hep-ph/0611358`), and embedding the RS1 model within a little Higgs framework (`hep-ph/0206021`

)[1]. Alternately, one can ignore the electroweak Hierarchy Problem and use the RS framework as a solution to the little Hierarchy problem (see `0802.0203` and references therein). These 'little RS' models can be used for flavor and electroweak precision while invoking some other solution to the Hierarchy problem. In this sense they are the 'opposite' of the RS + little Higgs models where the warped geometry solves most of the Hierarchy and the little Higgs solves the remaining little Hierarchy.

- **Variant signatures from top to bottom:** Finally, it is worth remarking that although the RS framework can be realized within 'warped throat' compactifications in string theory, one generically expects additional light states coming from stringy excitations. These can appear as spin-2 Reggeon states, see `0907.3496` .

We now investigate some of the general phenomenology of these models, focusing on the features of 'realistic RS1' (bulk fields, mentioning some effects of custodial symmetry) and contrasting to the original RS1.

4 Spin-2

4.1 Original RS1 Model

The original RS1 model only had gravity propagating in the bulk. Since the SM is brane-localized, there is no KK tower for any SM field. Gravitons, on the other hand, have associated Kaluza-Klein states. The dominant signals for KK gravitons were decays into photons or leptons, $G^{(1)} \to \gamma\gamma, \ell\ell$. These are well studied (see, e.g. CMS EXO-10-019) and represent the usual experimental search for RS1.

4.2 Departures from RS

The point of this talk is that the phenomenology of *realistic* RS models are very different. When fields are pulled into the bulk, 4D couplings are determined by taking the overlap integral of the 5D profiles of each field. Heuristically, a 5D field is decomposed into a KK tower. Each tower $\phi^{(n)}$ state has a different 5D profile $f^{(n)}(z)$ (in a flat extra dimension these are sines or cosines):

$$\Phi(x,z) = \sum_n \phi^{(n)}(x) f^{(n)}(z).$$

The value of the $\phi^{(1)}\bar{\psi}^{(0)}\psi^{(0)}$ coupling depends on the 5D coupling constant and the overlap integral

$$\int dz\, \left(\frac{R}{z}\right)^a f_\phi^{(1)}(z) f_\psi^{(0)}(z) f_\psi^{(0)}(z).$$

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[1] Closely related to the little Higgs are the [holographic] composite pseudo-Goldstone Higgs models (`hep-ph/0412089`). In both cases the Higgs is a pseudo-Goldstone related to some global symmetry breaking. However, the composite Higgs models have a percent level tuning since the Higgs potential is generated at one-loop, whereas the symmetry structure of the little Higgs allows a natural separation between v and the global symmetry breaking scale f.

The (R/z) factor comes from the geometry; the precise power depends on the spin of the fields and is beyond the scope of this summary. The point, however, is that the form of these profiles also depends on the spin of the fields and the warped geometry leads to exponential (Bessel) profiles for the fermion fields. Note further that these profiles will satisfy orthogonality relations—the same orthogonality that exponentials exhibit in Fourier transforms.

It turns out that the profile of the zero mode spin-1 particle is flat. This means that the $G^{(1)} \to \gamma\gamma$ coupling vanishes in models with bulk fields. Further, the $G^{(1)} \to \ell\ell$ signatures are suppressed because the lepton profiles are exponentially small on the IR brane. The lesson is that the most realistic RS models have very different phenomenology from the original model and require different analyses. It is important to figure out the extent to which existing analyses can be used to constrain these models, and the extent to which these models suggest new analyses which would lead to general bounds on models of strong coupling (via the AdS/CFT correspondence).

4.3 KK Gravitons in realistic models

It turns out that KK gravitons are not likely to be the first mode in which new physics is discovered if an RS-like scenario is manifested in nature. Instead, a more generic signature is a spin-1 KK gluon. It is well known, however, that spin-determination will play a crucial role in determining the form of BSM physics: e.g. distinguishing SUSY (different spin partners) and XD (same-spin resonances). Thus it is worth noting the revised signatures of KK gravitons in the realistic RS model. For a good reference, see `hep-ph/0701150` .

The profile of the KK graviton is localized near the TeV brane, i.e. it is exponentially leaning towards the IR brane. This is precisely where the light fermions have exponentially small profiles (in order to pick up only a small part of the Higgs vev in their mass) so that it couples most strongly to the top quark (t_R in particular).

KK graviton mass. In the custodially protected model (which can relax strict constraints from electroweak precision observables) KK graviton mass is constrained by its contribution to the Peskin-Takeuchi S parameter which measures isospin violation. A rough model-dependent estimate is that $m_{G^{(1)}} \gtrsim 3$ TeV. However, there are model-building tricks (brane kinetic terms) that can lower this bound.

KK graviton production and decay. The dominant processes are

$$gg \to G^{(1)} \to f\bar{f} \tag{1}$$

$$gg \to G^{(1)} \to \phi\phi, \tag{2}$$

where ϕ is a scalar. These are components of the brane-localized Higgs doublet (h and the longitudinal components of the W and Z)[2]. A subdominant (by about an order of magnitude) production mode comes from W fusion, $qq \to q'q'WW \to q'q'G^{(1)}$. The decay of the KK graviton is dominated by scalars or tops depending on the choice of t_R localization.

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[2] One can consider models where the Higgs is in the bulk, but to solve the Hierarchy problem the Higgs profile must be very closely peaked on the IR brane

This is a free parameter since the SM top mass is fixed by the overlap of the t_R and t_L profiles.

A useful feature of the KK graviton is that the resonance is very narrow because other decay modes are 'volume suppressed' (from the overlap integral in the coupling), which helps against background. A good question is how much this narrow width is smeared out by invariant mass uncertainties.

The main signature to look for are resonances in *boosted tops*. In addition to SM background, there is some additional background from KK gluons (see below). In this model, however, the invariant masses of the KK gluon and KK graviton should be different by a factor of ~ 1.5 (modulo 'tricks' like brane kinetic terms). Further, one may hope to distinguish these using angular distributions. A rough estimate is that we expect sensitivity to $m_G < 2$ TeV with 100/fb, depending on boosted top tagging efficiency. (`0908.1968`)

Appeal: boosted tops. An important signature is boosted tops from a heavy resonance. This will require improved techniques for top identification. I will leave a detailed discussion of this to other talks, but we will make some comments below. (See also local work by Maxim Perelstein and students, `1111.6594` .)

The Higgs channel is more model-dependent but may also be important to distinguish against the KK gluon. The most promising signal is $G^{(1)} \to 2Z_L \to 4\ell$, for which we expect sensitivity to $m_G < 2$ TeV with 300/fb. (`0908.1968`)

5 Spin-1

For more on this, see Jay's talk on Friday. (I actually have no idea what Jay's talk will be about, but he said that he'll mention spin-1 resonances in RS/strongly coupled models.) This section is based on `hep-ph/0701166` and `hep-ph/0612015` .

5.1 KK Gluons

The most likely first signal of a bulk RS scenario are spin-1 KK gluon resonances. Even though spin-1 resonances are expected from generic strong coupling models, a KK *gluon* isn't required by generic composite models so that these would contribute to evidence towards an RS-like scenario. Like the KK graviton, the KK gluon has a profile leaning towards the IR brane—you should think about this as the first vibrational mode on a violin string, but now redshifted towards the IR brane. There is no $g^{(0)}g^{(0)}g^{(1)}$ (gluon–gluon–KK gluon) coupling because $g^{(0)}$ is flat and hence the overlap integral is zero by orthogonality. There is also no coupling to the Higgs states (h, $W_L^\pm$, Z_L), which is a good check that these states are indeed KK gluons.

We thus expect the KK gluon to couple dominantly to top quarks (t_R in particular). We are concerned with the cross section for

$$q\bar{q} \to g^{(1)} \to t\bar{t}.$$

Identifying top jets is crucial here since this signal is buried in the QCD dijet background otherwise.

Note that the KK gluon widths are broad due to the strong coupling, lading to additional problems for signal/background discrimination. (`hep-ph/0612015`) As a rough estimate, with 100/fb we may estimate a reach for $g^{(1)}$ at around 5 TeV. (`0908.1968`)

5.2 Boosted tops

These are just some comments from `hep-ph/0701166` . I am not an expert and am not sure what the current status is for the identification of boosted tops. For some more current discussion, see `1012.5412` .

- Standard top-tagging techniques (semi-leptoni cdecay) fail when the tops are very energetic, $\gtrsim 3$ TeV because the decay products are so collimated. These objects are difficult to distinguish from QCD jets. Distinguishing boosted tops from QCD jets is crucial.
- Forward top quarks tend to have more separated decay products (easier to have more $\Delta\phi$ and in the forward direction the boost has less effect on $\Delta\eta$). However, the SM $t\bar{t}$ background is also very forward and a strong p_T cut is usually needed to suppress this.
- For $M_{\text{KK}} \gtrsim 3$ TeV, only a few percent of the signal events will have an isolated lepton. Sufficiently large p_T cuts can beat down the background, but at the cost of low event rates.
- Technique: **Separation of b and ℓ**. For relatively light masses, $M_{\text{KK}} \lesssim 3$ TeV, one can demand separation between a tagged b and lepton. However, b tagging is difficult when the b is boosted.
- Technique: **Invariant mass**. One might try to use the invariant mass of a top jet to distinguish it from QCD jets, though a full study of massive jets (via off-shell partons and hard radiation) from QCD is required.
- Technique: **Substructure**. See David Krohn's talks at Cornell in 2011[3].
- Top identification will be more dependent on background rejection rather tahn signal efficiency.

5.3 Spin measurement

The s-channel production of a KK gluon leads to a $(1+\cos^2\theta)$ distribution in its rest frame. One can use this to identify the spin of the KK gluon by using the full angular acceptance of

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[3] `http://www.lns.cornell.edu/Events/JournalClub/rsrc/LEPP/Events/JournalClub/WinterSpring2011/TalkJC20110408_Krohn`

the central detector. One can afford to set high p_T cuts (e.g. 900 GeV) since the top p_Ts are $\sim M_{\text{KK}}/2$. This helps reduce the background, which is also strongly peaked forward along with the $(1+\cos^2\theta)$ distribution that one is looking for.

5.4 Spin correlation

We have emphasized that the KK gluon is most strongly coupled to right-chiral tops. Because these tops are boosted, the chirality eigenstate is approximately the same as the helicity eigenstate to $\mathcal{O}(m_t/E)$. Therefore one may use the measurement of the angular distribution of the ℓ^+ (forward-backward asymmetry) to determine the chirality of the $g^{(1)}t\bar{t}$ coupling. For a nice discussion, see Tim Tait's thesis `hep-ph/9907462` . (Some model-building has been attempted for the Tevatron $t\bar{t}$ forward-backward asymmetry.

5.5 KK Electroweak Bosons

KK excitations of the electroweak gauge bosons have lower production rates than KK gluons and tend to be more model-dependent. An interesting point here is that the KK Z contributes to the forward-backward asymmetry with an opposite sign as the SM Z since the KK Z couples dominantly to t_R rather than t_L. The KK EW bosons also have sizable decays to the Higgs and may also be produced via Z or W fusion.

In 'realistic models' with custodial symmetry to protect the T parameter (and also the $Z \to b\bar{b}$ coupling), there are additional Z' and W' states coming from the extended (custodial) gauge symmetry. See Peter Wittich's talk about W's in this workshop.

6 Spin-1/2

We will mostly ignore KK fermions since these have a small production cross section and masses that are heavier than the gauge KK modes. Custodial models have an enlarged particle content including states with exotic charges. This leads to contributions searches like same-sign dileptons. See `0908.1968` .

7 Spin-0

In all variants of the RS1 model, the solution to the hierarchy problem depends on a stabilization mechanism that separates the two branes to allow the geometry to warp down the IR scale[4]. Excitations about size of the extra dimension (the size modulus) are a scalar field in the theory called the **radion**. This can be identified with the scalar component of the 5D metric (which mixes with the 4D spin-2 part). In the conformal field theory this should be

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[4] This stabilization is the actual solution to the hierarchy problem, not the use of exponential coordinates which turn $\mathcal{O}(10)$ numbers into exponentially small numbers.

identified with the **dilaton**, the Goldstone boson of spontaneously broken scale invariance. For reviews, see `hep-ph/0110242` , `hep-ph/0002178` , `0705.3844]` .

The radion mass is given by the backreaction of the radius stabilizing scalar on the RS metric. This is cumbersome, but one can estimate the mass with respect to this backreaction as

$$m_r \sim (\text{backreaction})\frac{\mathcal{O}(\text{TeV})}{35}.$$

In the limit of zero back reaction this vanishes so that one can expect the radion to be the lightest state.

The radion $r(x)$ couples to the trace of the energy-momentum tensor, $\frac{1}{\Lambda}r(x)\Theta^{\mu}{}_{\mu}$. More technically, it couples to the things which break scale invariance. Classically, these are mass terms. Of course, we know that in the Standard Model the object which gives mass is the Higgs. So at the classical level, the radion couples just like the Higgs. In fact, the coupling is exactly proportional to the Higgs coupling, up to a scaling of v/Λ, where Λ is the RS cutoff scale. Thus the radion phenomenology is very similar to SM Higgs phenomenology.

At the quantum level there are additional terms which break scale invariance. You know this because the Standard Model has nonzero β-functions. Thus, in addition to copies of the Higgs couplings, the radion couples to massless gauge bosons through the trace anomaly. Effectively this gives a coupling of the radion to photons and gluons proportional to the β function of those gauge groups. For QCD this is large so that the radion production can be enhanced at the LHC.

In the realistic RS models with bulk gauge fields there is also an additional tree-level coupling to the gauge bosons. This is a big difference from the original RS1 model since once the fields are pulled into the bulk, bulk zero mode gauge boson is not peaked on the TeV brane and hence there is no limit in which this reproduces the original RS1 set up.

Properties: for light radion masses, the branching fraction into gluons is large. The $b\bar{b}$ and $\gamma\gamma$ branching ratios are suppressed relative to the SM Higgs. At large radion masses the couplings become similar to the SM Higgs. Is there a radion at 125 GeV? (Ask Csaba, Jay, and Javi.)

8 Variants

In my talk I have a few extra slides on RS variants. These are meant as filler and I encourage the interested reader to pursue these topics with the usual review literature. The Cornell's hep-ph group is a source of local expertise.

9 Other references

- Some basic theory introductions: `hep-ph/0404096` , `hep-ph/0510275`
- Review of phenomenology: `0908.1968`