Planck'06

Radion phenomenology with bulk fields in a warped extra dimension

Seung J. Lee

Cornell University

With Csaba Csaki and Jay M. Hubisz

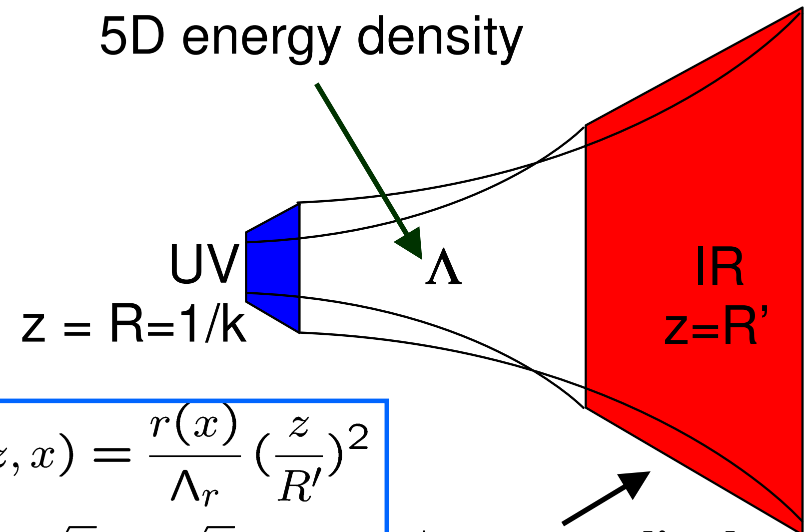
Based on work in progress

Outline

- Warped XD and Radion
- SM fields localized on IR brane
- SM fields in the bulk
- Higgs in the bulk
- Summary

Warped XD and Radion

- RS scenario with one XD
  - XD curved, but brane remains static and flat.
  - Address hierarchy problem



Assume we live here

(red shift to TeV scale)

$$
\begin{aligned}
ds^2 &= \left(\frac{R}{z}\right)^2 \left(e^{-2F}\eta_{\mu\nu} - (1+2F)^2 dz^2\right) \\
&= e^{\underbrace{-2k\,y}_{\text{warp factor}}-2F}\eta_{\mu\nu} - \underbrace{(1+2F)}_{}{}^2 dy^2
\end{aligned}
\qquad
F(z,x) = \frac{r(x)}{\Lambda_r}\left(\frac{z}{R'}\right)^2
\qquad
\Lambda_r = \frac{\sqrt{6}}{R'} = \frac{\sqrt{6}}{R} e^{-k\,r_0}
$$

warp factor

Radion as a metric fluctuation

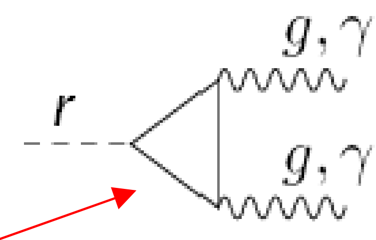
- Radion (fluctuation in the distance of two brane)
  - Radius must be stabilized (i.e. GW mechanism)
  - Radion is one of the most interesting discovery channels
    - Radion could be the lightest new particle
    - In some scenarios, radion would be the only visible new particle
  - Higgs-Radion mixing can change Higgs signals at LHC

SM fields localized on IR brane

- Most phenomenological studies for radion are limited for this scenario so far. (original RS model)
- Higgs-radion kinetic mixing arises from curvature-scalar mixing term. $\boxed{\int d^4x\sqrt{g_{ind}}\,\xi\, R(g_{ind})\, H^\dagger H}$
  - Mixing parameter ξ is a free parameter
- Radion interactions $\boxed{\frac{r}{\Lambda_r} T^\mu_\mu}$
  - with fermions and massive gauge bosons:

$$\boxed{\mathcal{L} = \frac{r}{\Lambda_r}\left(2M_W^2\, W^+_\mu\, W^{\mu -} + M_Z^2 Z_\mu\, Z^\mu\right)}$$

Giudice, Rattazzi, Wells



  - with massless gauge bosons: $\frac{r}{\Lambda_r}\left[b_3 - \frac{1}{2}F_{1/2}(\tau_t)\right]\frac{\alpha_s}{8\pi}G^a_{\mu\nu}G^{\mu\nu\, a}$

$$\frac{r}{\Lambda_r}\left[(b_2 + b_Y) - (F_1(\tau_W) + \frac{4}{3}F_{1/2}(\tau_t)\Big))\right]\frac{\alpha}{8\pi}F_{\mu\nu}F^{\mu\nu}$$

Beta function from trace anomaly

SM fields in the bulk

- More realistic models have SM fields in the bulk:
  - SM fields localized on the IR (TeV) brane has problem with four fermion operator. $\boxed{\frac{\lambda}{\Lambda_{TeV}^2}\bar{\psi}_{SM}\psi_{SM}\bar{\psi}_{SM}\psi_{SM}}$

    → $\Lambda_{TeV} > 10^3$ TeV (first 2 generations) → Need additional structure: i.e. flavor symmetry
  - From AdS/CFT picture, it is more natural to put fields into bulk.
  - Can describe fermion mass hierarchy by bulk profiles.
  - Can address the gauge coupling unification.
  - Many interesting phenomenological models using this implementation.

    Realistic RS: Agashe, Delgado, Sundrum,…

    Composite Higgs: Agashe, Contino, Pomarol, Servant…

    Higgsless: Cacciapaglia, Csaki, Grojean, Terning,…

    etc…(Gherghetta,…)
- **To address hierarchy problem, Higgs still needs to be localized near the IR brane**

SM fields in the bulk

SM fields localized on IR brane: coupling is proportional to 4D mass of a particle

- Radion interactions:

$$S_{\text{radion}} = \int \sqrt{g}\left[-F\left(\text{Tr } T^{MN} - 3T^{55}g_{55}\right)\right] \longleftrightarrow T^{\mu}_{\mu} F\big|_{z=R'}$$

- Radion interactions with Fermions:
  - Couplings to the radion are dependent on bulk profiles.
    - For $c_R > -½$ and $c_L < ½$ (localized near IR brane) $\left.\right\}$ $-\frac{m}{2\Lambda_r}\left(\frac{5+6c_R}{3+2c_R}+\frac{5-6c_L}{3-2c_L}\right)$
    - For $c_R < -½$ and $c_L > ½$ (localized near UV brane) $\left.\right\}$ $\frac{m}{\Lambda_r}(c_R - c_L)$
  - The new effect is ~20% compared to the case when all SM fields are localized on the IR brane. (model-dependent)
  - These couplings enter into the calculation of radion-gauge boson couplings

SM fields in the bulk

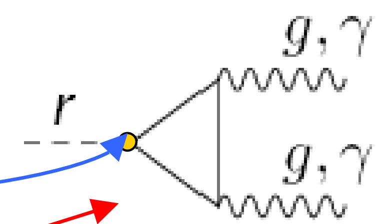
• Radion interactions with Gauge bosons

Rizzo;

Csaki, Hubisz, SJL

- New tree level effective 4D couplings from the bulk
  - For r →γγ, this contribution is large.
- For massless gauge bosons, contributions from both trace anomaly and loop diagrams are also important.
  - KK states effects for these two contribution mostly cancel each other:

$\underbrace{b^f_3 = -2/3 \text{ and } F_{-1/2} = -4/3}$ => 0 (decoupled)



bulk effect from fermion sector

r→ gg:

$$\frac{r}{\Lambda_r}\left\{ b_3^G + \sum_{m>0} B_m \overbrace{\left[b_3^{\mathrm{KK}} - \frac{3}{2}F_1(\tau_m^G)\right]}^{\text{gluon KK states}} + \sum_{f,m\geq 0} B_{fm}\overbrace{\left[b_3^f - \frac{1}{2}F_{1/2}(\tau_{fm})\right]} - \frac{2\pi}{\alpha_s \log\frac{R'}{R}}\right\}\frac{\alpha_s}{8\pi}G^a_{\mu\nu}G^{\mu\nu\, a}$$

with $b_3^G = 11$, $b_3^{\mathrm{KK}} = 21/2$, and $b_3^f = -2/3$

β-function from trace anomaly

Tree level bulk effect

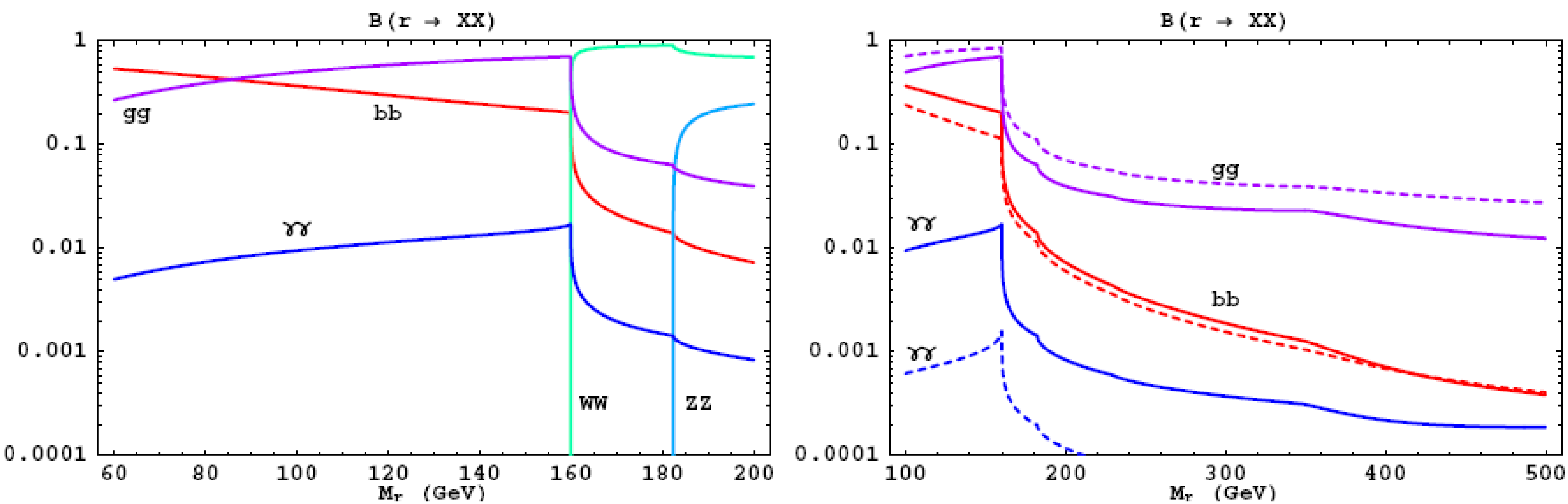
–For r →γγ, similar formula for the effective couplings. But, new tree level bulk contribution is relatively large.

–For the massive gauge bosons, couplings proportional to mass are dominant over new effect.

SM fields in the bulk

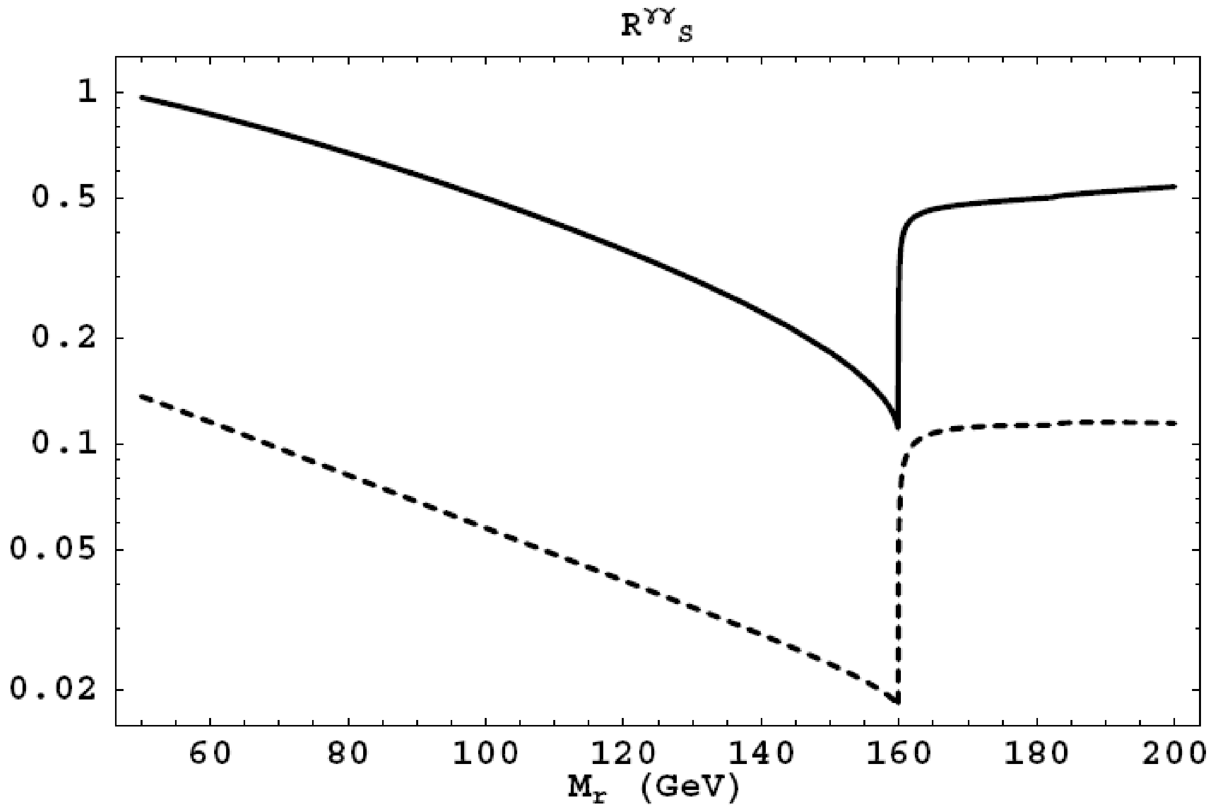
- Branching fractions (preliminary)
  - Branching fractions of the radion into on-shell final states are changed for every decay mode.
  - Radion to two photon decay enhanced by factor 10 (blue line).

(Note: Higgs-Radion mixing not yet included.)



SM fields in the bulk

- **Significance Plot**
  - This figure displays the ratio of the discovery significance for the radion to that of a Higgs boson of the same mass in the $\gamma\gamma$ channel.
  - In the shown ranges of radion mass, this ratio is increased by nearly a factor of 10 at some points. Λ_r is taken to be 10 TeV in this plot.



Higgs in the bulk

Chang, Hisano, Nakano, Okada, Yamaguchi;

Davoudiasl, Lillie, Rizzo;

Csaki, Hubisz, SJL

- Motivation
  - From the view point of AdS/CFT, Higgs cannot be completely localized on the IR brane

    (complete localization implies an infinite anomalous dimension for the fermion condensate on the CFT side)
  - In order to solve the hierarchy problem, Higgs still needs to be localized near the IR brane, and most phenomenology doesn't change due to the smearing of Higgs into bulk.
  - However, Radion is also localized near the IR brane:

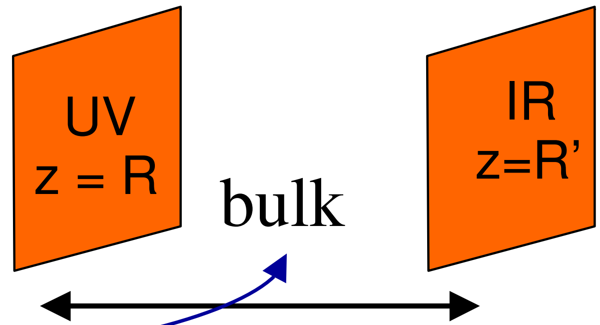
    Higgs-Radion mixing can be different from the case of Higgs being completely localized on the IR brane.

Higgs in the bulk

- Implications of Higgs being in the bulk
  - Would it be possible to stabilize the modulus (radius) using the bulk Higgs?
    - It is not possible to stabilize the modulus and solve the hierarchy problem at the same time using the bulk Higgs alone.
    - To have a minimum in the bulk Higgs potential, we need to have a sizable VEV at the Planck brane, comparable to that on IR brane. However, having this kind of Higgs VEV will reintroduce the hierarchy
  - If not, would modulus stabilization be affected by the bulk Higgs?
    - We have checked using superpotential method that including the bulk Higgs does not change the modulus stabilization, or the radion mass.
    - We also checked that warped geometry doesn't change, and also that radion solution doesn't change. (small backreaction limit is still valid)

Higgs in the bulk

Work in progress…



Higgs potential is localized on the IR brane

- **Higgs potential**

$$S_{\text{higgs}} = \int d^4x dz \sqrt{g} \left(\overbrace{g^{MN}(D_M H)^\dagger (D_N H) + m_{bulk}^2 H^\dagger H} - \overbrace{\frac{1}{\sqrt{g_{55}}} \delta(z - R') \lambda_T (H^2 - v_T^2)^2} \right)$$

- **Higgs-radion mixing: from 5D Ricci scalar**

$$\int d^5x \sqrt{g} \xi H^\dagger H R_5 \qquad R_5 = 20k^2 + 2e^{6ky} F'^2(x) + 2e^{4ky} F''^2(x) + \cdots$$

Resulting 4D effective Lagrangian:

mass redefinition

$$\tilde{m}_{bulk}^2 = m_{bulk}^2 + \frac{20\xi}{R^2}$$

$$\mathcal{L} = -\frac{1}{2} h \Box h - \frac{1}{2} m_h^2 h^2 - \frac{1}{2} (1 + 6\xi (\frac{v_{SM}}{\Lambda_r})^2 A) r \Box r - \frac{1}{2} m_r^2 + 6\xi \frac{v_{SM}}{\Lambda_r} B h \Box r - 2 \frac{v_{SM}}{\Lambda_r} \left(m_{bulk}^2 R^2 + 20\xi \right) r h$$

$$A = 2 \frac{R^4}{R'^4} \int dz \frac{z}{R} \phi^2(z) = 0.3 - 0.6$$

$$B = \frac{2}{3} \frac{R^2}{R'^2} \int dz \frac{R}{z} \phi^2(z) = 0.17 - 0.24$$

Kinetic mixing modified:

For SM fields localized on the IR brane, **A = B = 1**

Mass mixing:

New effect!

Summary

- Radion could be the most interesting discovery channel for Warped XD models.
- Most interesting models have SM particles in the bulk.
- Radion phenomenology is different from original RS case. In some cases, branching fractions can differ by ~ factor 10.
- Higgs-radion mixing can be different.
- Work in progress…