(review of) Radion Physics at the LHC

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Outline

• Introduction
• The radion in RS1
• radion with matter in bulk
• Higgs-radion mixing
• Some preliminary results
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Introduction

Is it the Higgs?

- Radion couplings are higgs-like (except to gluons and photons)
- Radion might be the lightest new particle in warped scenarios
- When matter in the bulk, KK modes are constrained to be at \( \sim 3 \) TeV. The radion could be the only accessible mode from these models, or perhaps could even be used as a discovery channel for some of the heavy KK modes (1st KK graviton?).
- Radion can in principle mix with the Higgs
[Randall, Sundrum, ('98)]

[Charmousis, Gregory, Rubakov ('99)]

[Golberger, Wise ('99)]

[Csaki, Graesser, Lisa Randall, Terning ('99)]

[Giudice, Rattazzi, Wells (00)]

[Csaki, Graesser, Kribs (00)]

[Han, Kribs, McElrath ('01)]

[Rizzo, Hewett ('02)]

[Dominici, Gunion, Grzadkowski, MT ('02)]

[Gunion, MT, Wells ('03)]

[Csaki, Hubisz, Lee ('07)]
The Radion and its interactions

In the RS1 model [Randall,Sundrum,(’98)] the background metric $g_{AB}^o$ is defined by

$$d s^2 = e^{-2 \sigma} \eta_{\mu \nu} \, dx^\mu dx^\nu + dy^2$$

with $\sigma(y) = ky$ and such that a hierarchy is created between the two boundaries at $y = 0$ and $y = \pi r_0$ is created.

The linear metric perturbations $h_{AB}(x, y)$ can be reduced to

$$d s^2 = (e^{-2 \sigma} \eta_{\mu \nu} + [e^{-2 \sigma} h^{TT}_{\mu \nu}(x, y) - \eta_{\mu \nu} r(x)]) \, dx^\mu dx^\nu + (1 + 2e^{2 \sigma} r(x)) \, dy^2$$

[Charmousis,Gregory,Rubakov(’99)]

⇒ linear interactions of radion and gravitons with matter but NOT quadratic i.e.

$r-\psi-\psi$, $r-V-V$ but NOT $r-r-V-V$
We propose the metric perturbations (only radion)

\[ ds^2 = \eta_{\mu\nu} \left( e^{-2\sigma} - r(x) + \frac{1}{4} e^{2\sigma} r^2(x) \right) dx^\mu dx^\nu + \left( 1 + 2 e^{2\sigma} r(x) + 2 e^{4\sigma} r^2(x) \right) dy^2 \]

such that in the gravity Lagrangian there are NO \( r \partial r \partial r \) terms

\[ \text{[Gunion,MT,Wells(03),MT(04)]} \]

\( r(x) \) does not have a potential. A stabilization mechanism is actually required (for example [Golberger,Wise('99)])

**INTERACTIONS**

Computing radion interactions is computing graviton interactions:

We write the previous metric as

\[ g_{AB} = g_{AB}^{(0)}(y) + g_{AB}^{(1)}(y) r(x) + g_{AB}^{(2)}(y) r^2(x) \]
Matter-gravity interactions come from the matter action

\[ S_{\text{mat}} = \int d x^5 \sqrt{-g} \mathcal{L}_{\text{mat}} \]

To expand this action in powers of the metric perturbations, we use

\[ \frac{\delta S_{\text{mat}}}{\delta g^{AB}} = \frac{1}{2} \int d x^5 \sqrt{-g} T_{AB} \]

and

\[ \frac{\delta^2 S_{\text{mat}}}{\delta g^{CD} \delta g^{AB}} = \frac{1}{2} \int d x^5 \sqrt{-g} \left( \frac{\delta T_{AB}}{\delta g^{CD}} - \frac{1}{2} T_{AB} g_{CD} \right) \]
And obtain

\[ S_{\text{mat}}(r^0) = \int d\mathbf{x}^5 \sqrt{-g^{(0)}} L_{\text{mat}} \]

\[ S_{\text{int}}(r) = -\frac{1}{2} \int d\mathbf{x}^5 \sqrt{-g^{(0)}} e^{2\sigma} \left( -T^{\mu}_{\mu} + 2T_{55} \right) r(x) \quad \text{[Rizzo(02), Csaki, Hubisz, Lee(07)]} \]

\[ S_{\text{int}}(r^2) = \frac{1}{2} \int d\mathbf{x}^5 \sqrt{-g^{(0)}} \left[ e^{4\sigma} \left( 4T_{55} - \frac{1}{4} T^{\mu}_{\mu} \right) + g^{AB}_{(1)}(y) g^{CD}_{(1)}(y) \frac{\delta T_{AB}}{\delta g^{CD}} \right] r^2(x) \]

where \( g^{AB}_{(1)} = e^{2\sigma} \left( -g^{AB}_{(0)} + 3 \delta^A_5 \delta^B_5 \right) \)

But the radion \( r(x) \) is NOT canonically normalized (canonical kinetic term).

The canonically normalized radion is \( \phi_r(x) \frac{2}{\Lambda_r} = e^{2k\pi r_0} r(x) \)

where \( \Lambda_r = \sqrt{6} M_{Pl} e^{-k\pi r_0} \)
RS1 - Matter on the brane

Single radion interaction becomes

\[ S_{int}(r) = \frac{1}{\Lambda_r} \int d^4x T^\mu_\mu \phi_0(x) \]

\[ \Rightarrow \text{Higgs-like couplings!} \]

For vector fields we have

\[ \mathcal{L}_{int} = \frac{1}{\Lambda_r} \phi_0(x) \left[ M_V^2 V^\alpha V_\alpha + \epsilon \left( \frac{F^{\alpha\beta} F_{\alpha\beta}}{4} - \frac{M_V^2}{2} V^\alpha V_\alpha \right) \right] \]

Dimensional regularization \( D = 4 - \epsilon \). Here \( \epsilon \) comes from the trace.

\( \Rightarrow \) If \( M_V = 0 \) (gluons, photons) the \( \epsilon \) term will cancel with the \( \frac{1}{\epsilon} \) divergent terms from loops of charged fields.

\( \Rightarrow \) Interactions with massless gauge bosons: The higgslike 1-loop contribution + this trace anomaly
\[ \text{gluons} \quad - \frac{\alpha_s}{8\pi} \left[ \sum_i F_{1/2}(\tau_i)/2 - b_3 \right] \frac{\phi_0}{\Lambda_r} G_{\mu\nu}G^{\mu\nu} \]

\[ \text{photons} \quad - \frac{\alpha}{8\pi} \left[ \sum_i e_i^2 N_c^i F_i(\tau_i) - (b_2 + b_Y) \right] \frac{\phi_0}{\Lambda_r} F_{\mu\nu}F^{\mu\nu} \]

\[ \text{massive bosons} \quad \frac{\phi_0}{\Lambda_r} M_V^2 V^\alpha V_\alpha \]

\[ \text{fermions} \quad \frac{\phi_0}{\Lambda_r} m_f \bar{f} f \]
(from K.Cheung (’00))
Branching ratio

(from K.Cheung ('00))
Figure 1: Ratio of signal significance in the $\gamma\gamma$ and $ZZ$ channels between the radion and a SM higgs of same mass

(from Giudice,Rattazzi,Wells(’00))
The Radion and Matter in the bulk [Csaki, Hubisz, Lee(07)]

With gauge fields and fermions in the bulk (but Higgs on the TeV brane) we need the new interactions with the radion.

\[ S_{int}(r) = -\frac{1}{2} \int dx^5 \sqrt{-g^{(0)}} e^{2\sigma} (\mathcal{T}_\mu - 2T_{55}) r(x) \]

For Massless gauge fields:

- The \( T_{55} \) term \( \Rightarrow \) tree level coupling \( r \)-glu-glu and \( r \)-\( \gamma \)-\( \gamma \).
- Brane localized kinetic terms for gauge fields.
- Trace anomaly effect
- Loop contributions (tops and W’s)

\[
\left[ 1 - \frac{4\pi \alpha (\tau^0_{UV} + \tau^0_{IR})}{4\kappa \pi r_0} \right] + \frac{\alpha}{8\pi} \left( b - \sum_i \kappa_i F_i(\tau_i) \right) \frac{\phi}{\Lambda_r} F_{\mu\nu} F^{\mu\nu}
\]
• Radion interaction with Massive Gauge bosons maintains its main contribution from the boson mass

• Interaction with fermions, although model dependent remains proportional to the mass of the fermion with an $\mathcal{O}(1)$ coefficient

• Interaction with the higgs is computed as in RS1 since Higgs localized
Figure 2:

(from Csaki, Hubisz, Lee ('07))
Figure 3: Ratio of signal significance in the $\gamma\gamma$ and $ZZ$ channels between the radion and a SM higgs of same mass (from Csaki, Hubisz, Lee ('07))
Higgs-radion mixing

[Giudice, Rattazzi, Wells (00), Csaki, Graesser, Kribs (00), Han, Kribs, McElrath (01),
Rizzo, Hewett (02), Dominici, Gunion, Grzadkowski, MT (02)], Gunion, MT, Wells (03)]...

We now consider the brane operator:

\[ S_\xi = \xi \int d^4 x \sqrt{g_{\text{ind}}} R(g_{\text{ind}}) \ H_0^\dagger H_0. \]

\[ \mathcal{L}_{\text{scalar}} = -\frac{1}{2} \left\{ 1 + 6 \xi \left( \frac{v_0}{\Lambda_r} \right)^2 \right\} \phi_0 \Box \phi_0 - \frac{1}{2} \phi_0 m_{\phi_0}^2 \phi_0 \]

\[-\frac{1}{2} h_0 (\Box + m_{h_0}^2) h_0 - \frac{6 \xi v}{\Lambda_r} h_0 \Box \phi_0 \]

Radion mass added “by hand”.
NORMALIZED HIGGS AND RADION PHYSICAL FIELDS

\[ h_0 = \left( \cos \theta - \frac{6 \xi \gamma}{Z} \sin \theta \right) h + \left( \sin \theta + \frac{6 \xi \gamma}{Z} \cos \theta \right) \phi \equiv d \ h + c \ \phi \]

\[ \phi_0 = \left( - \cos \theta \ \frac{1}{Z} \right) \phi + \left( \sin \theta \ \frac{1}{Z} \right) h \equiv a \ \phi + b \ h \]

with \[ \tan 2\theta \equiv 12 \gamma \xi Z \frac{m^2}{m^2_{\phi_0} - m^2_{h_0} (Z^2 - 36 \xi^2 \gamma^2)} , \]

and \[ Z^2 \equiv 1 + 6 \xi \gamma^2 (1 - 6 \xi) \quad \text{and} \quad \gamma \equiv \frac{v_0}{\Lambda_r} . \]
Figure 4:
(from Dominici, Gunion, Grzadkowski, M.T. ('02))
VV and ff COUPLINGS

\[ g_{ZZh} = \frac{g M_z}{c_W} (d + \gamma b) \quad g_{ZZ\phi} = \frac{g M_z}{c_W} (c + \gamma a) \]
\[ g_{f\bar{f}h} = -\frac{g m_f}{2 M_w} (d + \gamma b) \quad g_{f\bar{f}\phi} = -\frac{g m_f}{2 M_w} (c + \gamma a) \]

Very interesting property of the $\xi$-mixing: the different couplings of the physical radion to matter photons, gluons, fermions and massive bosons can vanish at different points in parameter space.

\[ \Rightarrow \phi \text{ can be photon-fobic, gluon-fobic or massive-fobic} \]
Figure 5:
(from Dominici, Gunion, Grzadkowski, M.T. ('02))
(from Dominici, Gunion, Grzadkowksi, M.T. ('02))
Precision EW constraints

[Csaki, Graesser, Kribs(00), Gunion, MT, Wells(03)]

COMPUTATION OF S AND T:

Figure 6: One-loop contributions to $S_h$ and $S_\phi$
\[ S = -S_{h_{SM}}^{ref} + S_h + S_\phi + S^A + S^{ren} \]

\[ T = -T_{h_{SM}}^{ref} + T_h + T_\phi + T^A + T^{ren} \]

- \( S^A \) finite anomalous contribution from the trace anomaly
- \( T^A \) finite anomalous contribution from the trace anomaly
- \( S^{ren} \) from the running of operators like: \( \frac{1}{\Lambda^2} H^+ W_{\mu\nu} B^{\mu\nu} H \)
- \( T^{ren} \) from the running of operators like: \( \frac{1}{\Lambda^2} |H^+ D_\mu H|^2 \)
Figure 7: S-T dependence on $\xi$ and Higgs Mass
(from M.T. ('04))
Figure 8:

(from Gunion, M.T., Wells ('03))
Figure 9: Branchings of the radion vs. its mass $M_\phi$
Figure 10: Branchings of the radion vs. its mass $M_\phi$
Figure 11: Branchings of the radion vs. its mass $M_\phi$
Conclusions

• radion phenomenology is very similar to higgs search
• RS1 radion is simple and well studied
• Higgs-radion mixing adds interesting properties to the radion (fobic couplings)
• Bulk matter has interesting effects in radion pheno
• more so if in conjunction with some radion-higgs mixing (preliminary). A thorough scan of parameter space should be done, as well as perhaps a new estimate of effects on oblique corrections by the $\xi$ mixing in the bulk fields scenario.
• a “non-standard” scalar, hypothesized to be the radion, could be used as an alternative search channel for elusive heavy KK modes..