Bulk Scalar Mixing in Randall Sundrum Models

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Outline

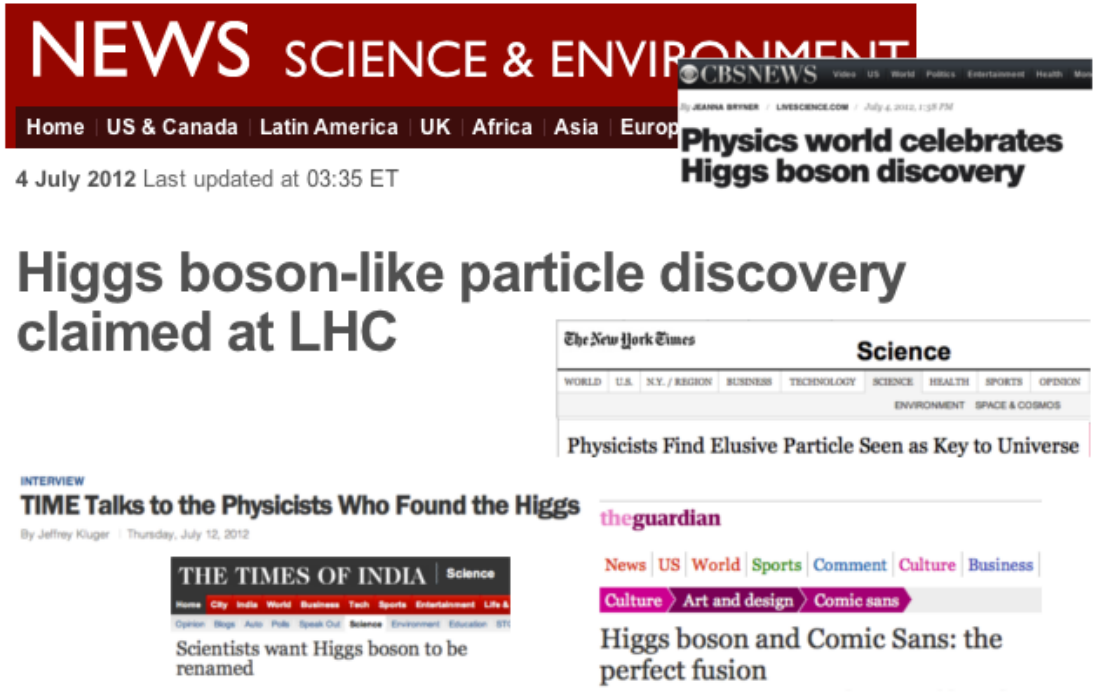
Motivation: Higgs and RS

Theory of Bulk Higgs-Radion Mixing

Phenomenology and Constraints

Conclusions

The Discovery

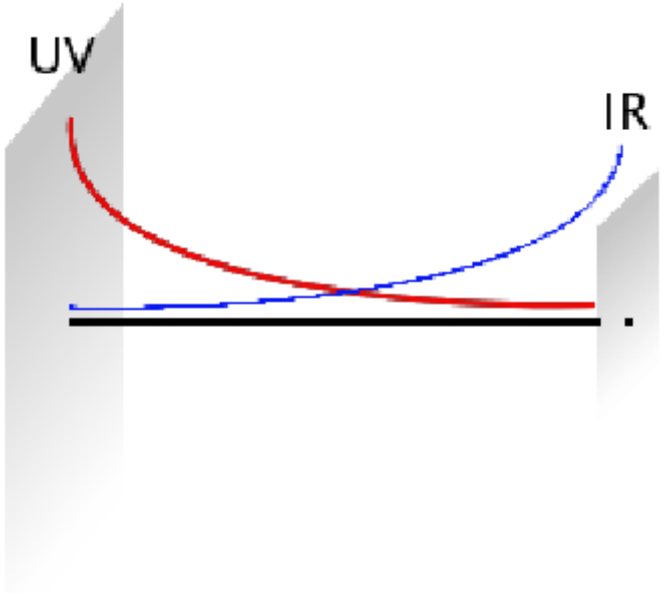


- Higgs Excited People In and Out of Physics
- Our Questions:
  - The Higgs or A Higgs?
  - How does Higgs Constrain BSM?

Warped Extra Dimensions

Randall-Sundrum Models

- Model of Flavour
  - Fermion Localisation
- Solves Hierarchy Problem
  - Gravitational redshift
- AdS-CFT $\rightsquigarrow$ Computable Composite Higgs



$$\mathrm{d}s^2 = \mathrm{e}^{-2ky}\mathrm{d}x^\mu\,\mathrm{d}x_\mu - \mathrm{d}y^2$$

The Radion

- New degree of freedom:
  Fluctuations in Size of
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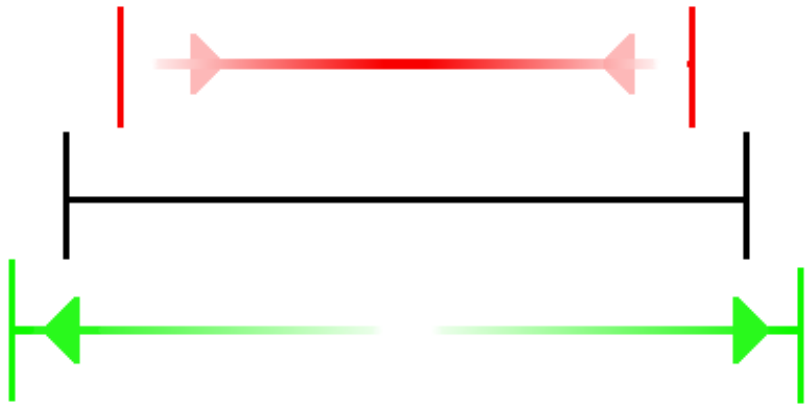

$$\mathrm{d}s^2 = \mathrm{e}^{-2ky-2G}\mathrm{d}x^\mu\,\mathrm{d}x_\mu - (1+2G)^2\mathrm{d}y^2$$

- Radion is Scalar $\Rightarrow$ Can Mix with Higgs
- Lightest new state $\Rightarrow$ Massless in pure RS
- Mass requires stabilisation : $\mathrm{e}^{2ky} \to \mathrm{e}^{2ky} + \mathcal{O}(m^2_{rad})$

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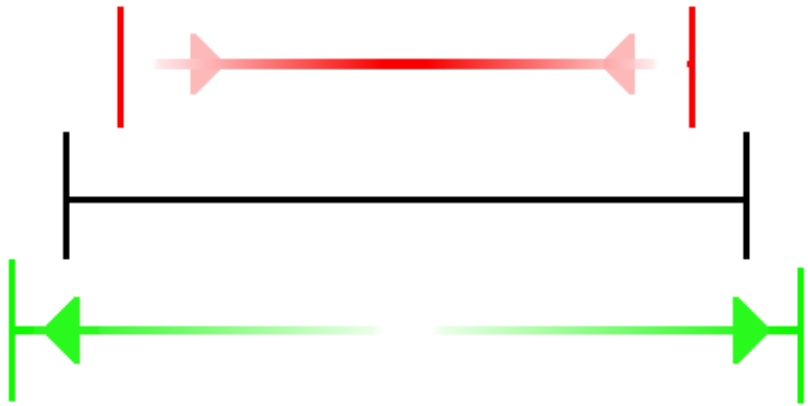

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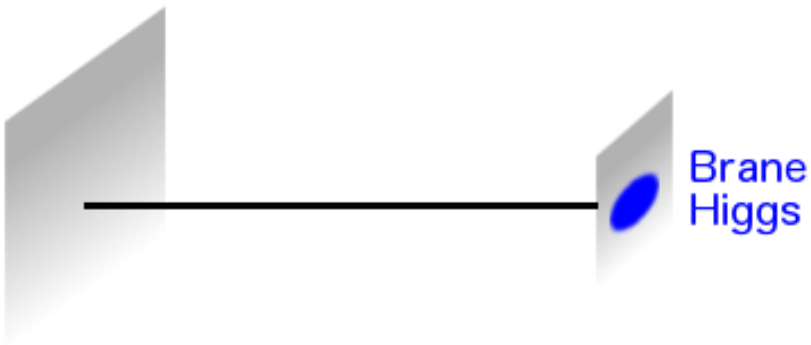
Bulk and Gauge Higgs

Where to put Higgs?

Usual case: Brane Higgs



- Kinetic Higgs-Radion Mixing

Our case: Bulk Higgs

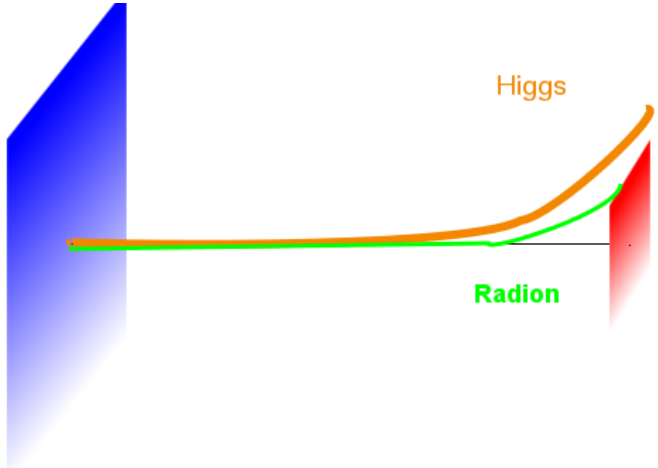
- Mass and Kinetic Mixing
- Different radion decays
- Possible motivation: Gauge-Higgs Unification

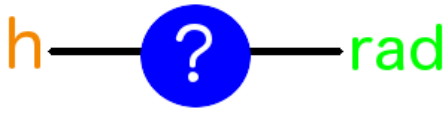
Statement of Intent

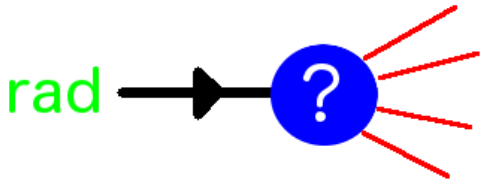
Set-Up

RS with two bulk scalars: Radion and

- Scalar Higgs; or
- Gauge-Higgs







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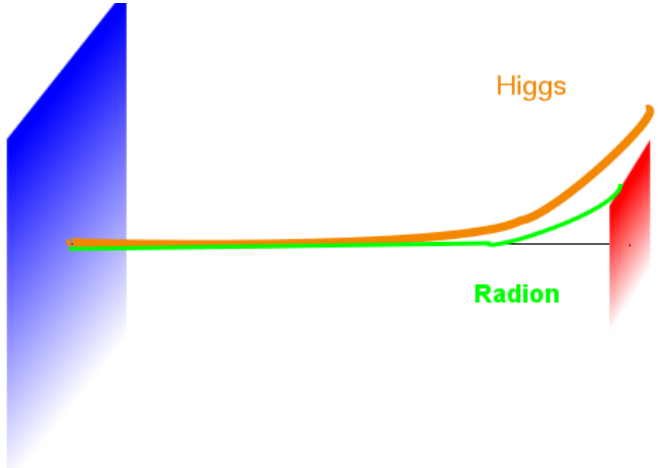

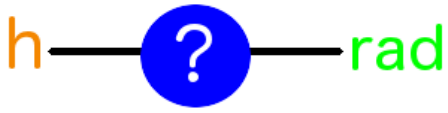

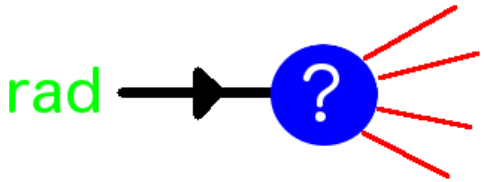

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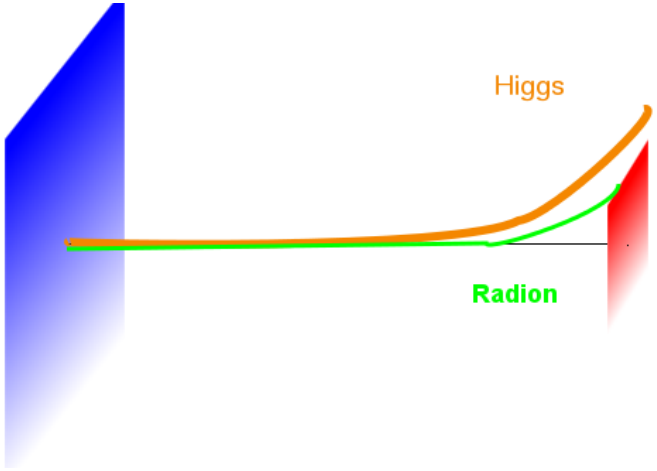

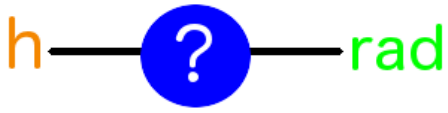

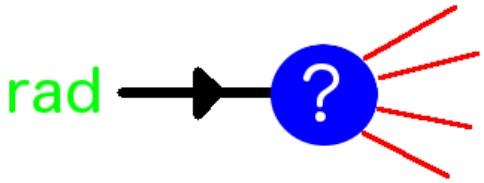

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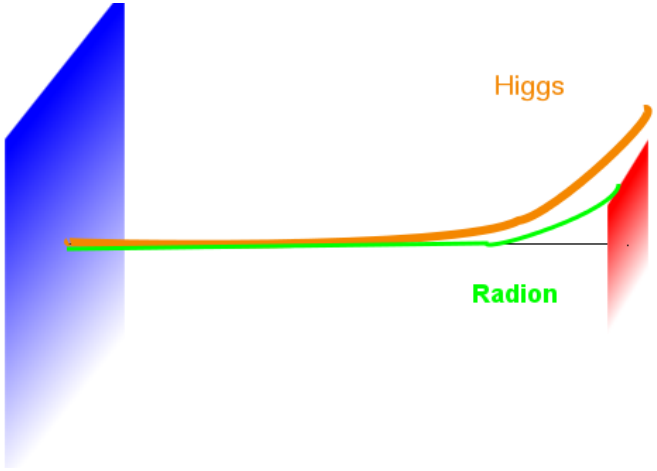

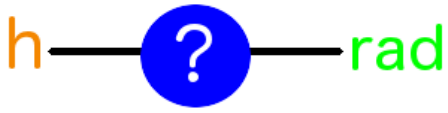

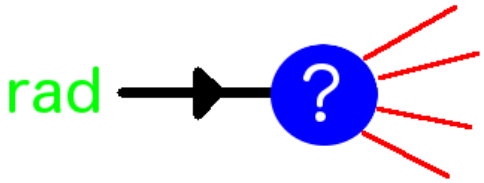

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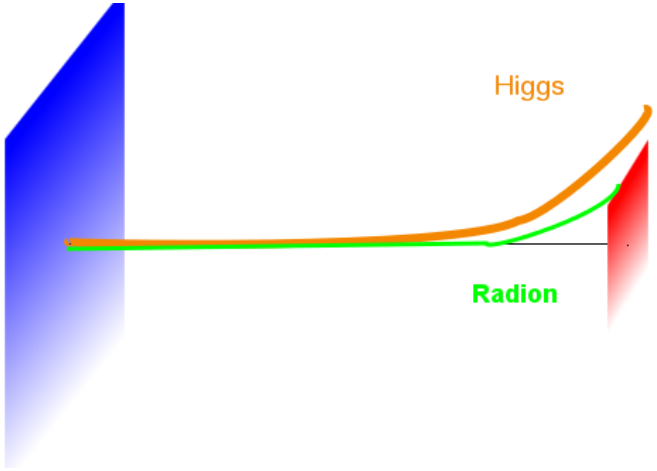

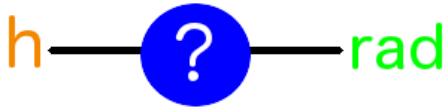

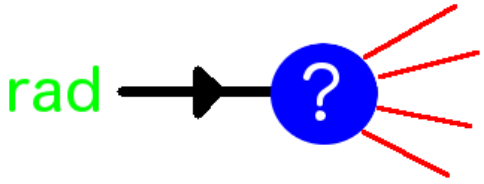

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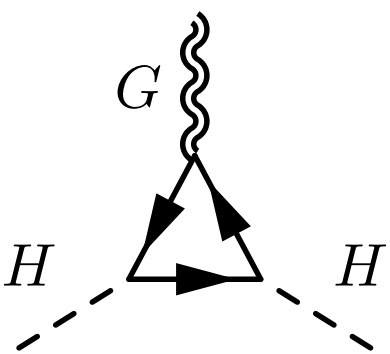
Higgs-Radion Mixing

Two Possible Sources:

Curvature Scalar

- Explicit Mixing
- $\xi\, R_5\, H^\dagger H$
- 4D: $\xi = \frac{1}{6}$ for conformality
- Radiatively generated:



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Radion $\subset$ Metric

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- Kinetic terms g^{yy}
- Volume element $\sqrt{g}$

Absent for brane Higgs:

- No $\partial_y v$ term
- So mixing term

$$\mathcal{L}_{mix} \propto G\, h \left.\frac{\delta V}{\delta h}\right|_{h=v} = 0$$

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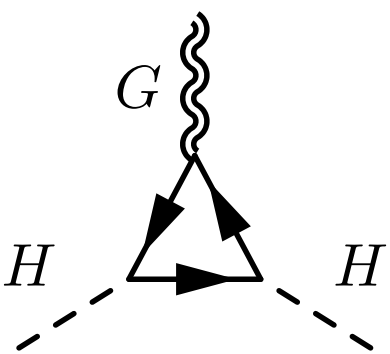

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Bulk and Brane

Brane

- Induced metric, curvature:
  $R_4\, H^\dagger H \equiv R_4(g^{ind}_{\mu\nu})\, H^\dagger H$
- $R_4 = \partial\partial h + \ldots \sim \Box G + \ldots$
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$$\mathcal{L}_{mix} = \xi \sqrt{\frac{2}{3}} \frac{v}{\Lambda_r} (\partial^\mu h)(\partial_\mu r)$$

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- Same terms in 5D Curvature
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Curvature Mass

Bookkeeping:

- Scalar curvature non-zero in RS
$$R_5 = 20\,k^2 + \ldots$$
- Explicit mixing contains term like Higgs mass
- Easier to redefine into potential:

$$V(H) \to V(H) - \xi\, R^{bg}\, H^\dagger H$$
$$\mathcal{L}_\xi \to \xi\,(R - R^{bg})\, H^\dagger H$$

Vanishing Mass Mixing

$$G \propto \mathrm{e}^{2ky}; \qquad h(x,y) \propto v(y) \propto \exp\big[(2+\beta)ky\big]$$

Two Mass Mixings

- Explicit Mixing:

$$\mathcal{L}_\xi \supset \xi\, v(y)\, h(x,y)\, (G'' - 7k\, G' + 10k^2 G) = 0$$

- Implicit Mixing

$$\mathcal{L} \supset 2\, G\, v'\, h' - 2\, c_H^2 k^2\, G\, v\, h - 4\, G'\, v'\, h = 0$$

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Radion and Back-Reaction

- Calculations so far done for Massless Radion!

$$G(x,y) \propto \mathrm{e}^{2ky}$$

- Metric, radion profile, curvature tensors corrected $\mathcal{O}(m_{rad}^2)$

$$g_{\mu\nu} \propto \mathrm{e}^{-2ky} + \mathcal{O}(m_{rad}^2); \qquad G(x,y) \propto \mathrm{e}^{2ky} + \mathcal{O}(m_{rad}^2)$$

- Expect corrections $\rightsquigarrow$ mass mixing $\propto m_{rad}^2$
- Have shown in explicit model this is so

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An Effective Field Theory

Mixing Model Dependence:

1. Higgs profile (5D Mass) $\sim \mathcal{O}(1)$
2. Origin of radion mass $\sim \mathcal{O}(m_{rad}^2)$

So write

$$\mathcal{L}_{hr} = -c_1 \frac{v}{\Lambda_r}\left(h + \frac{1}{2v}h^2\right)\Box r + c_2 \frac{v}{\Lambda_r} m_R^2 \left(h\, r + \frac{1}{2v}\, h^2\, r\right)$$

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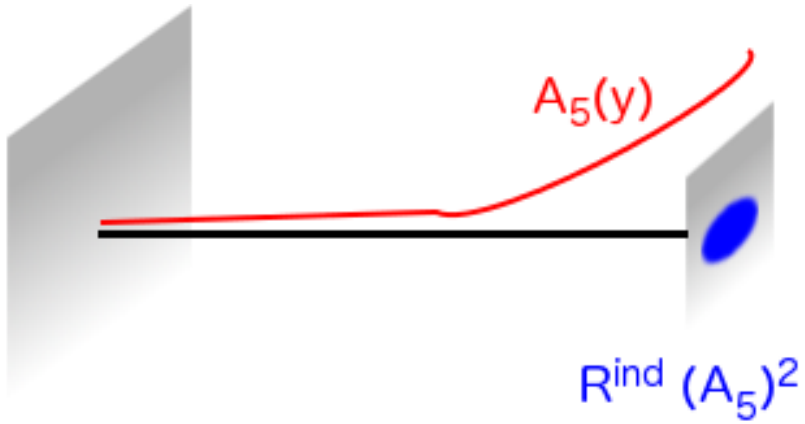
Mixing: Gauge-Higgs

- No Mixing in this case!
  - Explicit Mixing not gauge invariant:
    $$R_5 H^\dagger H \rightsquigarrow R_5 (A_5)^2$$
  - No gauge-invariant y-derivative
    $$F_{yy} = 0$$
- Can add Brane-localised Kinetic Mixing



- Radion phenomenology Still Different!

Radion Decays I

Vector Bosons

Brane Higgs

- Radion-W, Z coupling from Higgs kinetic term:

$$\sqrt{g_4}\, g^{\mu\nu} \left(\mathcal{D}_\mu H\right)^\dagger \left(\mathcal{D}_\nu H\right) \supset \left(1 - 4G\right)\left(1 + 2G\right) m_V^2\, V_\mu V^\mu$$

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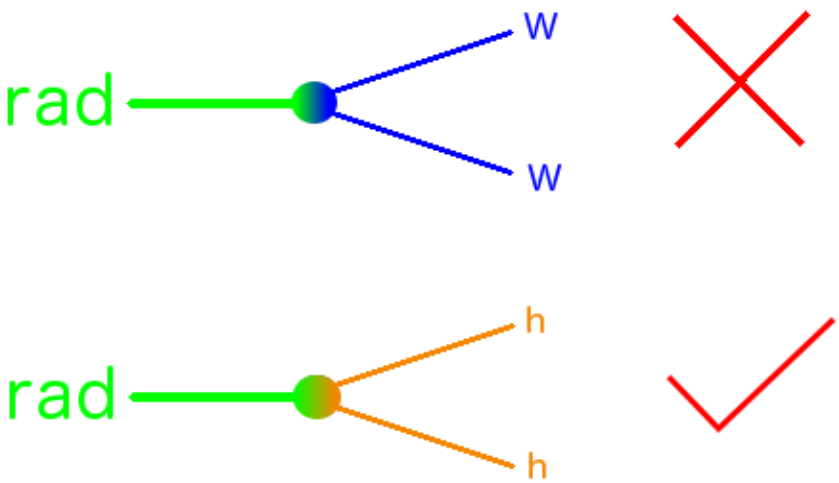
Radion Decays II

Higgs

Recall Higgs-Radion Cubic Couplings

- Interaction strength $\propto m_{rad}^2$
- Dominate for heavy radion
- Exist for Explicit and Implicit mixing



- $r \to hh$ also related to Heavy Higgs search
- Exists for brane Higgs, but coupling $\propto m_h^2$

Effect of Mixing

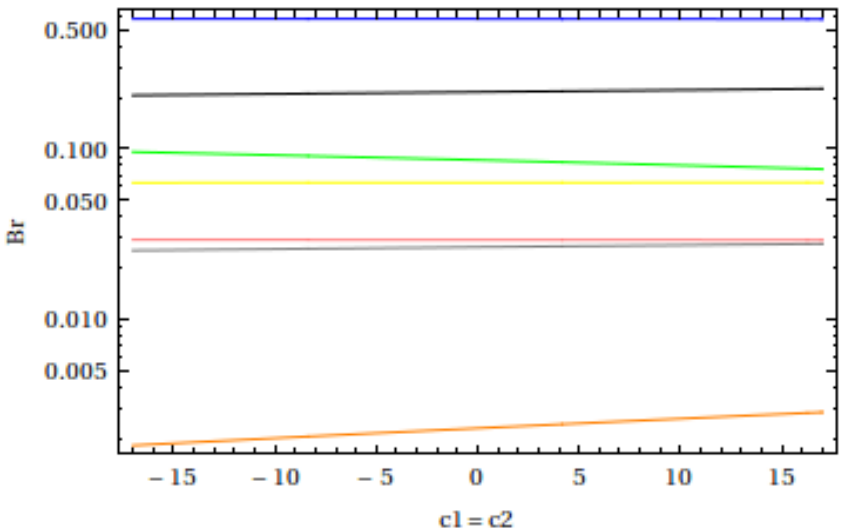
Effective Lagrangian

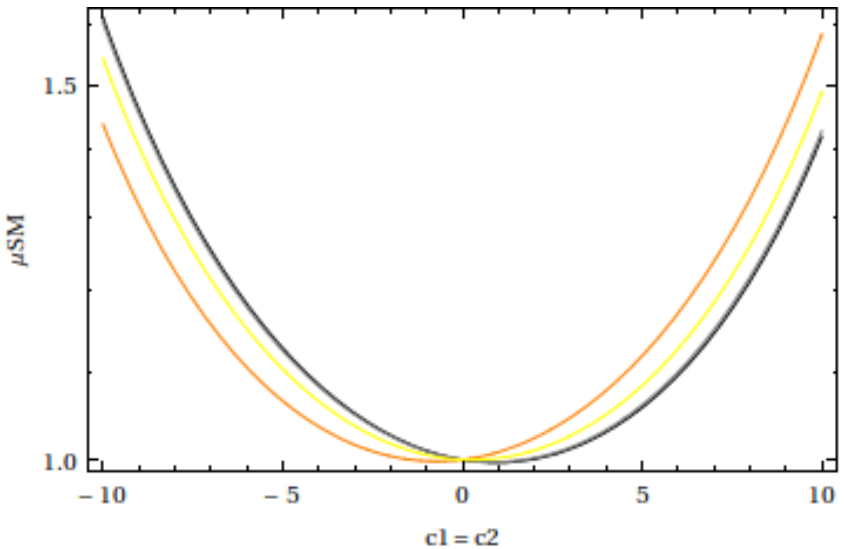
$$\mathcal{L}_{EFT} = \frac{1}{2}\left(\partial^\mu h\right)\left(\partial_\mu h\right) + c_1\,\frac{v}{\Lambda_r}\left(\partial^\mu h\right)\left(\partial_\mu r\right) + \frac{1}{2}\left(\partial^\mu r\right)\left(\partial_\mu r\right) - \frac{1}{2}\,m_H^2\,h^2 - c_2\,\frac{v}{\Lambda_r}\,m_R^2\,h\,r - \frac{1}{2}\,m_R^2\,r^2$$

- Diagonalise Kinetic Terms with non-Unitary transformation
- Diagonalise Mass Terms with Orthogonal Rotation
- Mass mixing angle $\theta \sim c_2 \dfrac{v}{\Lambda_r}$
- Does not vanish as $m_R \to \infty$

Higgs

Branching Ratios and Signal Strengths





$m_{rad} = 500$ GeV, $c_1 = c_2$

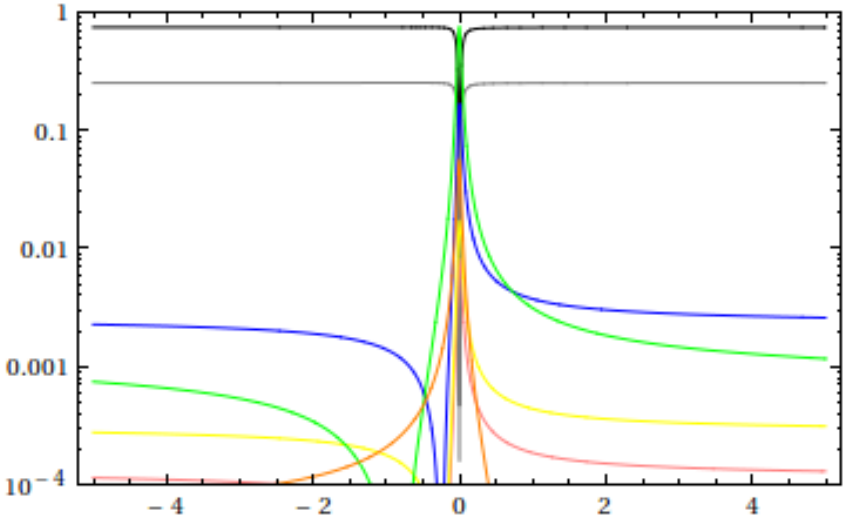
Black: W/Z; Blue: b; Yellow: τ; Green: g; Red: c; Orange: γ

- Asymmetry from Kinetic Mixing
- Signal Strength Increase from interplay of Mixings

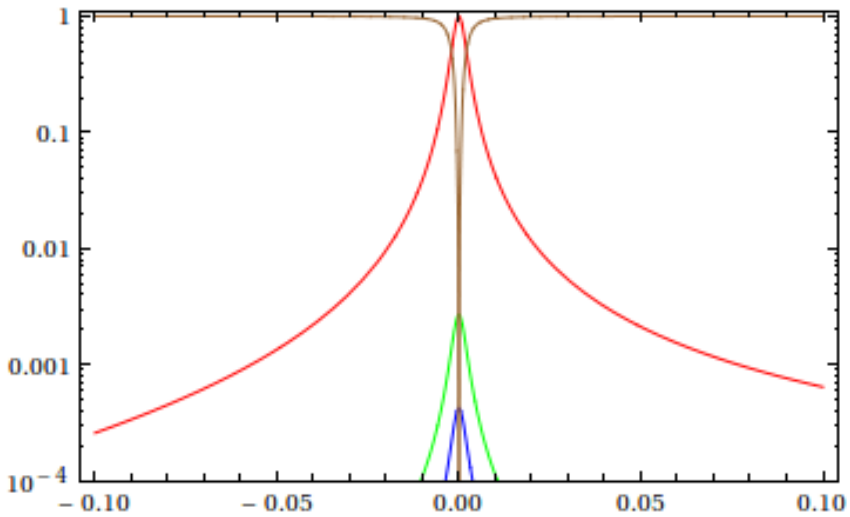
Radion

Branching Ratios

$m_{rad} = 200$ GeV:



$m_{rad} = 500$ GeV:



Black: W/Z; Brown: h, Blue: b; Yellow: τ; Green: g; Red: t; Orange: γ

- Decay to Higgses dominates when open
- Decay to W, Z Important through Mixing

LHC Constraints

Relevant Constraints

- Higgs Signal Strengths
- Heavy Higgs Searches
- $t\bar{t}$ Resonance Searches

- Scanning Model Space for Allowed/Excluded Points
- Preliminary Results thwarted by Software Issues . . .

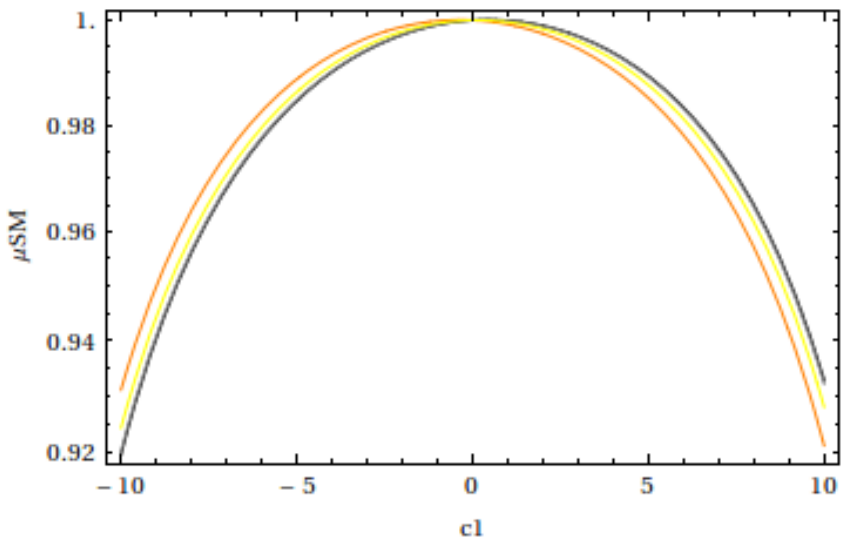
Look for Final Results soon!

Conclusions

- RS Bulk Higgs has both Mass & Kinetic Mixing with Radion
- Mass Mixing both Explicit and Implicit Origin
- Mass Mixing set by Radion Mass, still relevant as $m_{rad} \to \infty$
- Radion in Bulk/Gauge Higgs has No coupling to W, Z
- Constraining Radion Mass & Mixings with LHC results in Progress

Mixing Interplay

200 GeV:



500 GeV: