Bulk Scalar Phenomenology in Randall-Sundrum

arXiv: 1306.xxxx

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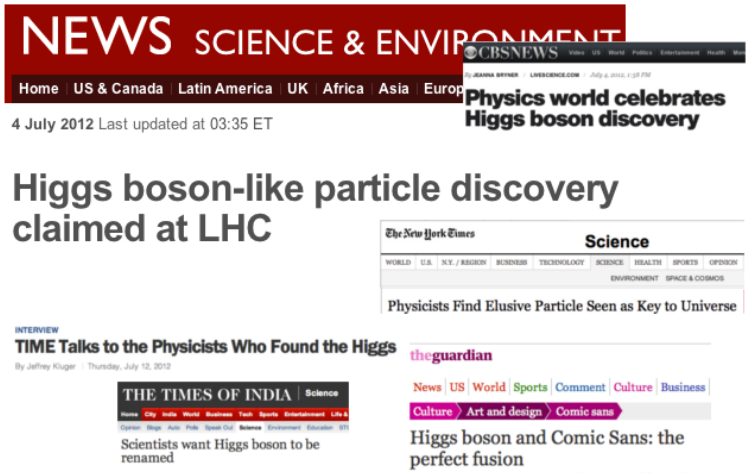
Outline

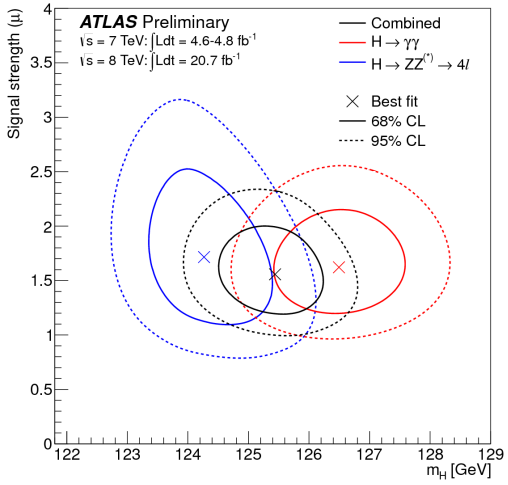
The Precision Higgs Era



- LHC discovery last July
  - Did you notice?
- Many Higgs couplings observed
- New era of particle physics

In particular:

- Higgs mass at percent level
- Coupling uncertainties shrinking
- Is everything post-GSW irrelevant?



Higgs Constraining BSM

Higgs measurements constraining deviations from SM:

Carmi *et al* 1202.3144, Low *et al* 1207.1093, Giardino *et al* 1207.1347, Ellis & You 1207.1693, Bonnet *et al* 1207.4599, Plehn & Rauch 1207.6108, Cacciapaglia *et al* 1210.8120, Belanger *et al* 1302.5694 And many more...

What distinguishes us?

- Specific, top-down model: Randall-Sundrum
- Kinetic and mass mixing from single coupling
- Interesting effects on Radion phenomenology
- Relate to full RS parameter space

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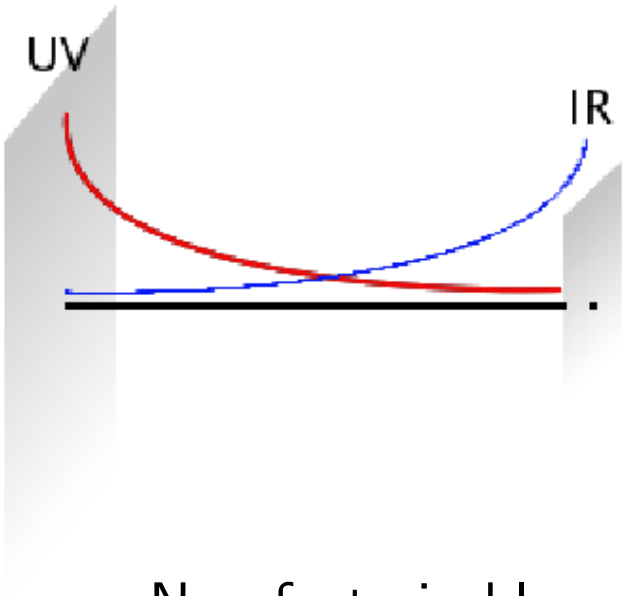
Randall-Sundrum Models

Brief Review



Warped Extra Dimensions:

- Popular BSM framework
- Model of Flavour Physics
- Solution to hierarchy problem:

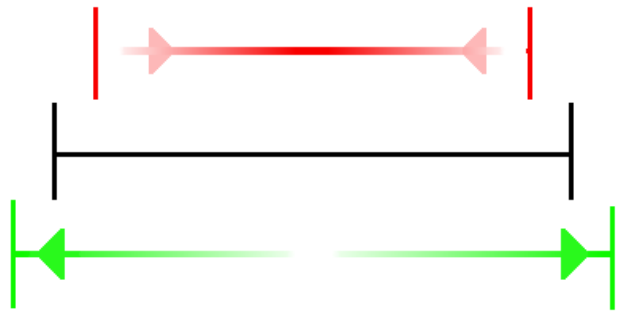
- Non-factorisable warping in fifth dimension
- Gravitational redshift exponentially lowers scales

$$\mathrm{d}s^2 = \mathrm{e}^{-2ky}\,\eta_{\mu\nu}\,\mathrm{d}x^\mu \mathrm{d}x^\nu - \mathrm{d}y^2 \quad \Rightarrow \quad \Lambda_{IR} \sim \Lambda_{UV}\mathrm{e}^{-kL}$$

AdS-CFT: IR-localised Higgs $\sim$ 4D composite Higgs

The Radion

- New scalar mode in all RS models
- Fluctuations in size of extra dim.
  (See cartoon ⇒)



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

- Typically very light, $m_r \ll m_{KK}$
  - Massless without stabilisation! *e.g.* Goldberger & Wise hep-ph/9907447
  - Neglect back-reaction in this talk: $G(x,y) \sim e^{2ky}$
  - Can be only new state observed
- Higgs-Radion mixing will be generic in RS models

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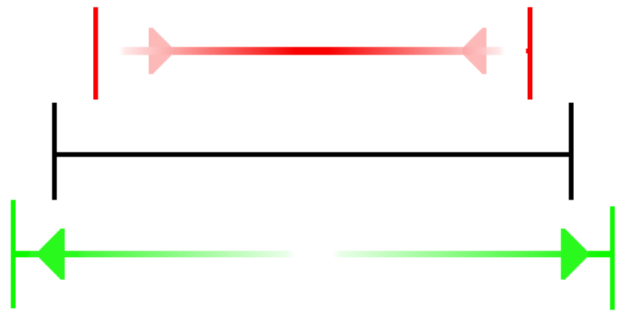

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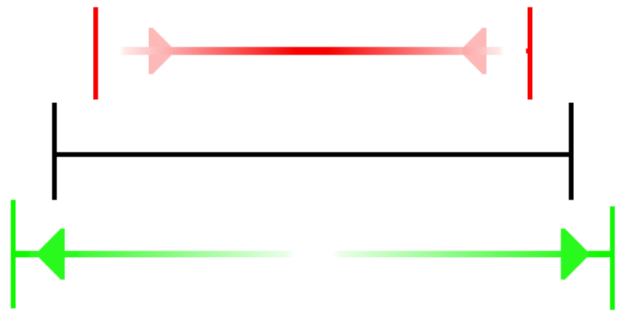

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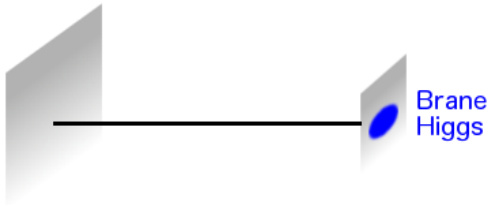
The Brane Higgs

Review

Usual RS approach: Higgs on brane

$$\int \mathrm{d}^5x\,\sqrt{|g|}\,\delta(y-L)\left[(D^\mu H)^\dagger D_\mu H - V(H)\right]$$



Canonical Higgs rescaling: Solution to Hierarachy Problem

$$H_{phys} = \mathrm{e}^{kL} H \qquad \Rightarrow \qquad m_{4D}^2 = \mathrm{e}^{-2kL} m_{5D}^2$$

SM masses brane-localised: Higgs couplings as SM

$$\int \mathrm{d}y\,\sqrt{|g|}\,\delta(y-L)\,Y_u \bar{Q}_L H u_R \quad \rightsquigarrow \quad m_u\left(1+\frac{h}{v}\right)\bar{u}u$$

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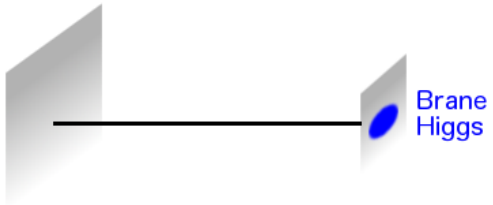

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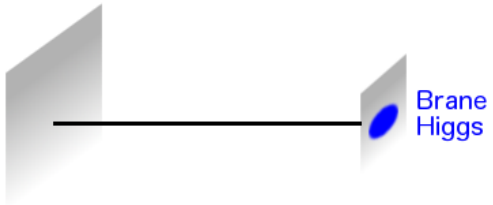

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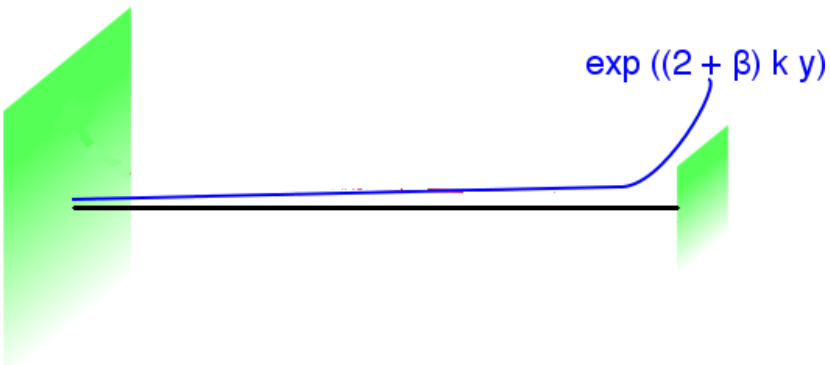
The Bulk Higgs

Alternative: Higgs in 5D Bulk.

$$\int \mathrm{d}^5x \sqrt{|g|} \left[(D^M H)^\dagger D_M H - V_{bk}(H) - V_{br}(H)\right]$$

Break symmetry only with IR potential: Solve hierarchy problem



- $\beta^2 = 4 + m_H^2/k^2$
- $v(y) \propto \mathrm{e}^{(2+\beta)ky}$
- $h^0(y) \propto v(y) + \mathcal{O}(\frac{m_h^2}{m_{KK}^2})$

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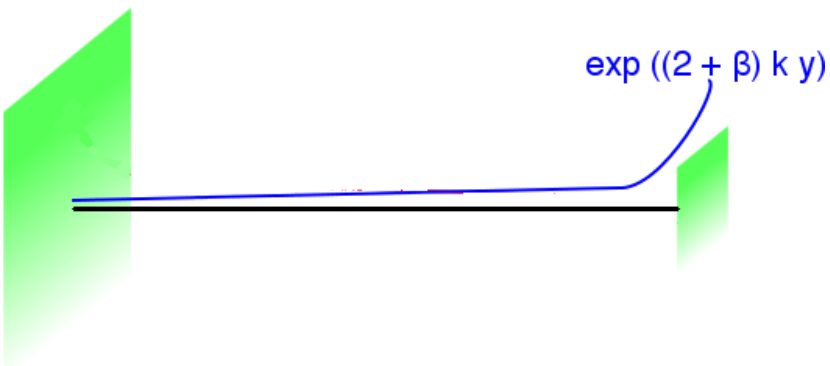

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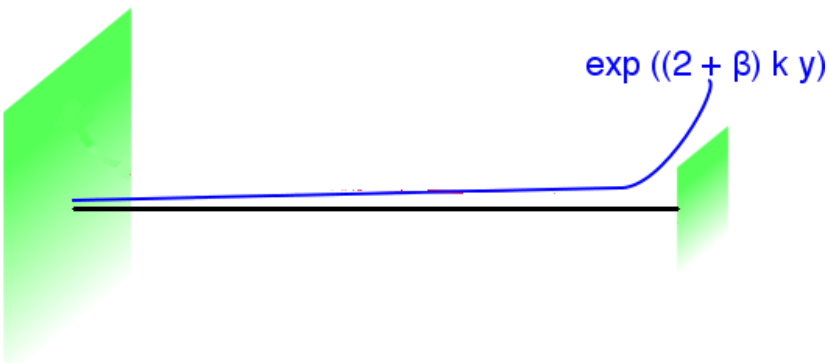

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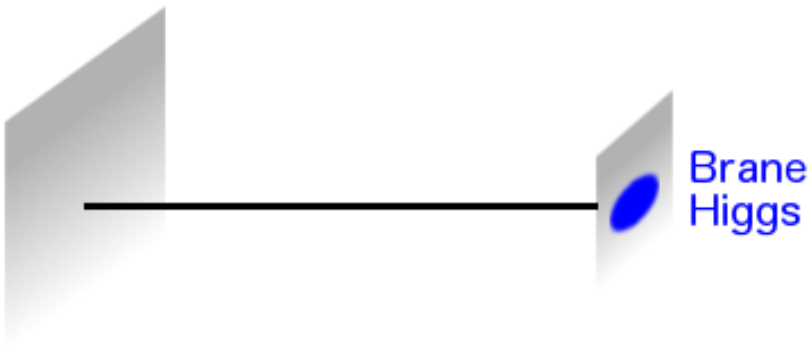
SM masses in bulk: Higgs couplings as SM

Bulk vs Brane Higgs

Brane Higgs:



- More predictive
- More studied
- Couplings as SM
- Kinetic Mixing with Radion
- Usual Radion couplings

Bulk Higgs:

- Generalisation of model
- More room to explore
- Couplings as SM
- Kinetic and Mass Mixing
- No Radion-WW coupling

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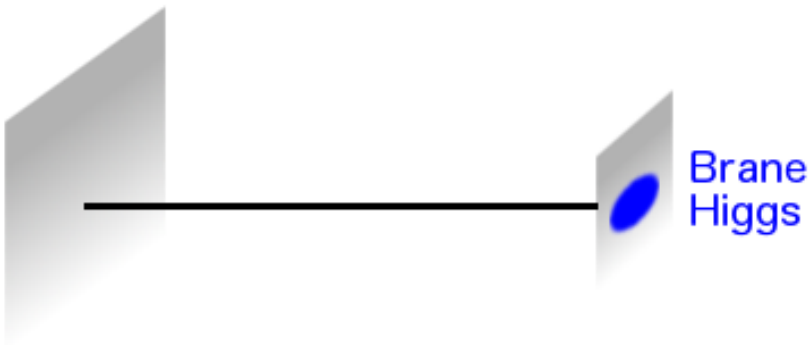

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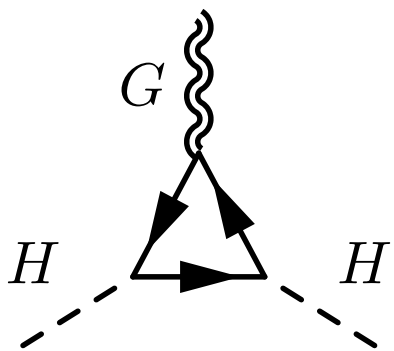
Origin of the Mixing

Radion $\subset$ metric: unique renormalisable mixing term

$$\mathcal{L}_{mix} = \xi\, R\, H^\dagger H$$

- Studied in 4D;
  $\xi = \frac{1}{6}$ required for $T_\mu{}^\mu = 0$
- Generated by top $(+\ldots)$ loops
- RS context:
  Exists both in bulk and on brane



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Treat size and sign of coupling as free parameter

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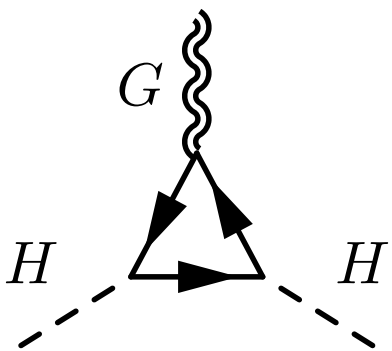

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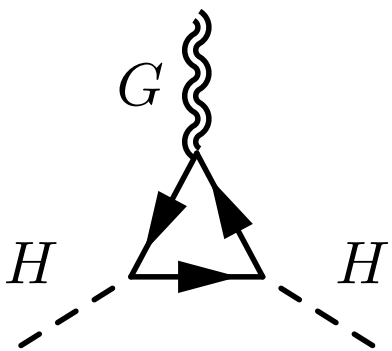

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Brane Mixing

Kinetic Mixing

On brane, must use induced metric, curvature

$$\mathfrak{g}_{\mu\nu}(x) = g_{\mu\nu}(x, L) = \mathrm{e}^{-2kL}\,\eta_{\mu\nu}\big(1 - 2G\big) + \ldots \qquad R_4 \equiv R(\mathfrak{g}) = -6\,\mathrm{e}^{2kL}\,\Box G + \ldots$$

- Induced mixing is pure kinetic

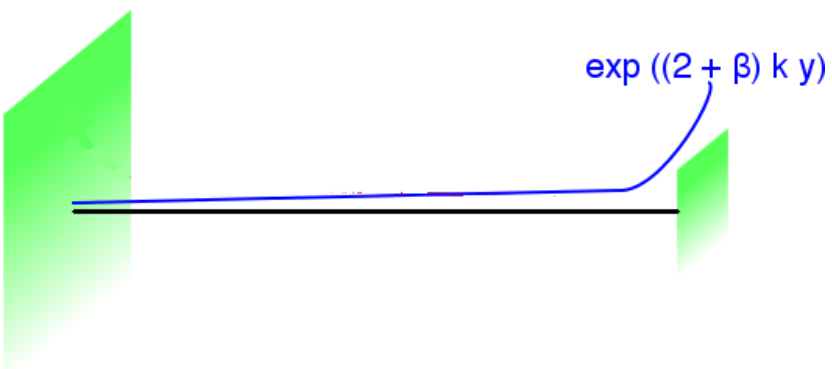
$$\xi\, R_4\, H^\dagger H \supset \sqrt{\frac{2}{3}}\,\frac{v}{M_{Pl}\,\mathrm{e}^{-kL}}\,\xi\,(\partial^\mu r)(\partial_\mu h^0)$$

Bulk Mixing I

Fiddling with the Profile

- $R \neq 0$ so mixing term $\Rightarrow$ Higgs Mass

$$-c_H^2\, k^2\, H^\dagger H + \xi\, R_5\, H^\dagger H = -(c_H^2 + 20\,\xi)\, k^2\, H^\dagger H + \ldots$$



- Shift: $\beta^2 = 4 + c_H^2 + 20\xi$
- VEV, Higgs profile unchanged as functions of β
- Note: mass parameter varies

Bulk Mixing II

Kinetic and Mass Mixing

Bulk mixing linear terms fun!

$$R_5 = \ldots + R^{MN}(\delta g)_{MN} + \nabla^M \nabla^N (\delta g)_{MN} - \nabla_M \nabla^M (\delta g)_N{}^N + \ldots$$

Kinetic Mixing:

$$\sqrt{\frac{2}{3}} \frac{1+\beta}{2+\beta} \frac{v}{M_{Pl} \mathrm{e}^{-kL}} \xi \, (\partial^\mu r)(\partial_\mu h^0)$$

Mass Mixing: (several contributions)

$$\sqrt{\frac{2}{3}} 2(1+4\beta) \frac{v}{M_{Pl} \mathrm{e}^{-kL}} (k \, \mathrm{e}^{-kL})^2 \, \xi \, r(x) \, h^0(x)$$

- Parametric suppression
- β-dependence
- Large mass scale $k \, \mathrm{e}^{-kL} \gg m_r, m_h$

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Diagonalisation

See Any Field Theory Textbook

Effective 4D theory:

$$\mathcal{L}_{mix} = \frac{1}{2}(\partial h^0)^2 + \xi\alpha(\partial h^0)(\partial r) + \frac{1}{2}(\partial r)^2 - \frac{1}{2}m_h^2(h^0)^2 - \xi\gamma\Lambda_{IR}^2 h\, r - \frac{1}{2}m_r^2 r^2$$

$$\alpha, \gamma \sim \frac{v}{M_{Pl}e^{-kL}}$$

$$\Lambda_{IR} = k\, e^{-kL}$$

$$\gamma = 0 \text{ (brane)}$$

- Kinetic mixing: Non-unitary transformation

$$r \to \tilde{r} - \xi\,\alpha\, h^0 + \mathcal{O}(\alpha^2)$$

- Mass mixing: Orthogonal rotation

$$\begin{pmatrix} r_m \\ h_m^0 \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \tilde{r} \\ h^0 \end{pmatrix}, \qquad s_\theta = 2\,\xi\,\gamma\,\Lambda_{IR}^2/m_r^2 + \mathcal{O}(\gamma^2)$$

- Note: linear approximation here for illustration only

Modified Couplings

In linear approximation

$$-\mathcal{L}_{int} = h^0\,\mathcal{O}_m + r\,\mathcal{O}_r$$

$$\rightarrow h^0_m \left[\mathcal{O}_m - \xi\left(\alpha + \gamma\,\frac{\Lambda^2_{IR}}{m^2_r}\right)\mathcal{O}_r\right] + r_m\left[\mathcal{O}_r + \xi\,\gamma\,\frac{\Lambda^2_{IR}}{m^2_r}\,\mathcal{O}_h\right]$$

- Higgs couplings contribution from both mixings
  - Couplings enhanced or suppressed (Sign of ξ)
- Radion couplings contribution from mass mixing only

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Radion Couplings

Relevant interactions: r–SM–SM

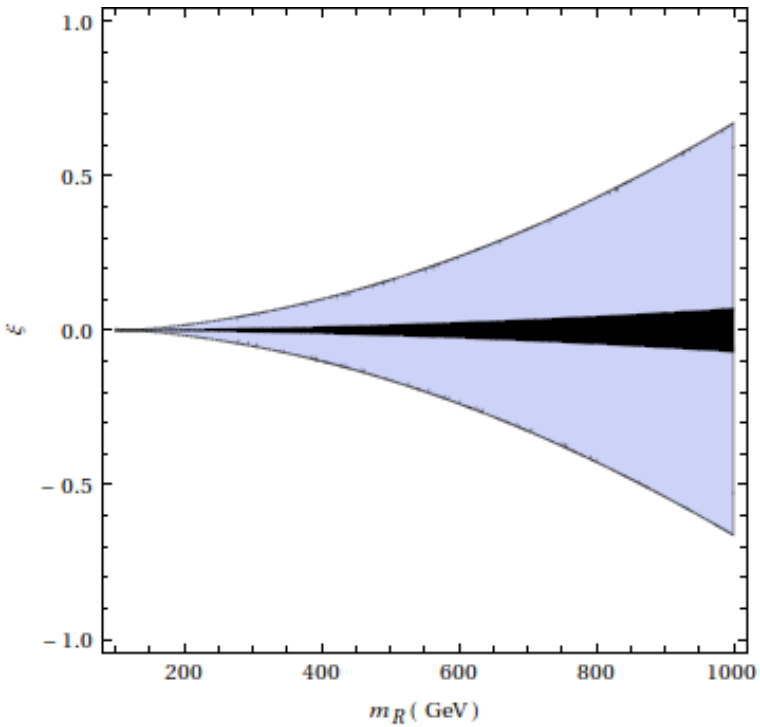
1. Kinetic terms:
   - Same for bulk and brane Higgs
   - Contribute to gluon and photon couplings:

$$\mathcal{L}_{int} \supset \frac{1}{8} F^{\mu\nu} F_{\mu\nu}\, r(x)\, \frac{1}{kL}\, \frac{1}{\sqrt{3} M_{Pl} \mathrm{e}^{-kL}}$$

2. Mass terms:
   - Different for bulk and brane Higgs
   - Bulk couplings β and $c_{L,R}$ dependent
   - Coupling to W, Z vanishes for bulk Higgs

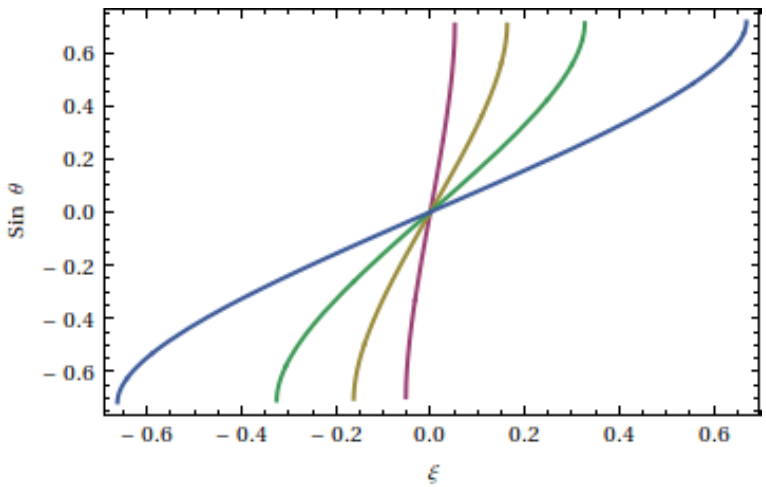
$$\begin{aligned}\sqrt{|g|}\, g^{\mu\nu} &= \left[\mathrm{e}^{-4kL}(1-2G)^2(1+2G)\right]\left[\mathrm{e}^{2kL}\,\eta^{\mu\nu}(1+2G)\right] \\ &= \mathrm{e}^{-2kL}\eta^{\mu\nu} + \mathcal{O}(G^2)\end{aligned}$$

Theoretical Mixing Limit



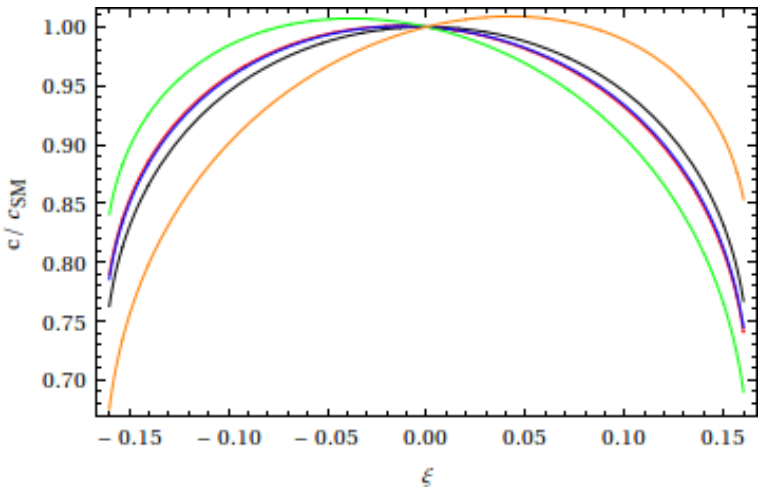
- Mixing increases radion mass
- Radion mass as input $\Rightarrow$ upper limit on $|\xi|$
- Shown: $\beta = 1$, $\Lambda_{IR} = 1$ TeV
- ($\Lambda_{IR} = 10$ TeV in black)
- Brane Higgs: much weaker limit

Scalar Mixing Angle



- Despite small ξ, large angle θ
- Shown: $\beta = 1, \Lambda_{IR} = 1$ TeV
- $m_r = 200$, 300, 500, 1000 GeV for red, yellow, green, blue lines

Higgs Couplings



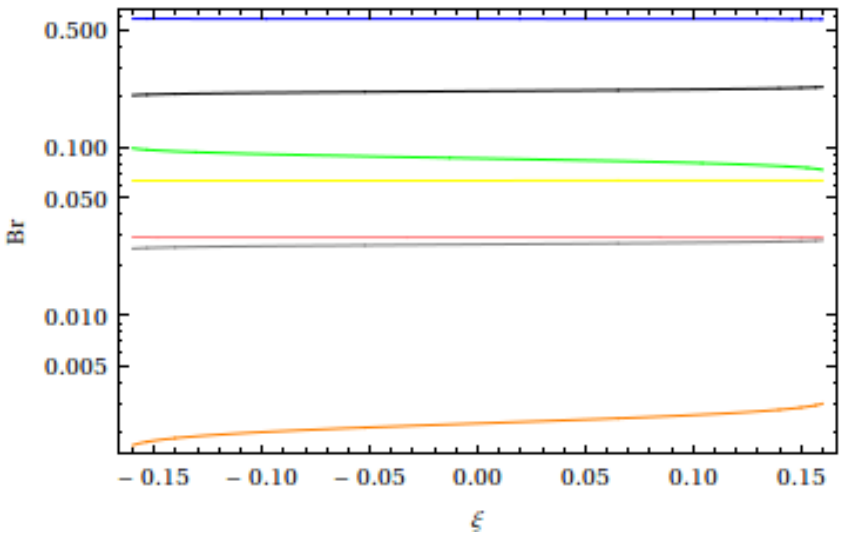
- Note asymmetry in ξ
- Mass mixing dominant; suppressing all couplings
- Kinetic mixing relevant for small $|\xi|$
- γ enhanced when other couplings suppressed

On same scale, brane Higgs couplings unchanged

($\beta = 1, \Lambda_{IR} = 1$ TeV, $m_r = 500$ GeV)

Black: W/Z; Red/Blue: t, b; Green: g; Orange: γ

Higgs Partial Widths



- Largest effects on g, γ
- Asymmetry in ξ

($\beta = 1, \Lambda_{IR} = 1$ TeV, $m_r = 500$ GeV)

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

Higgs Searches

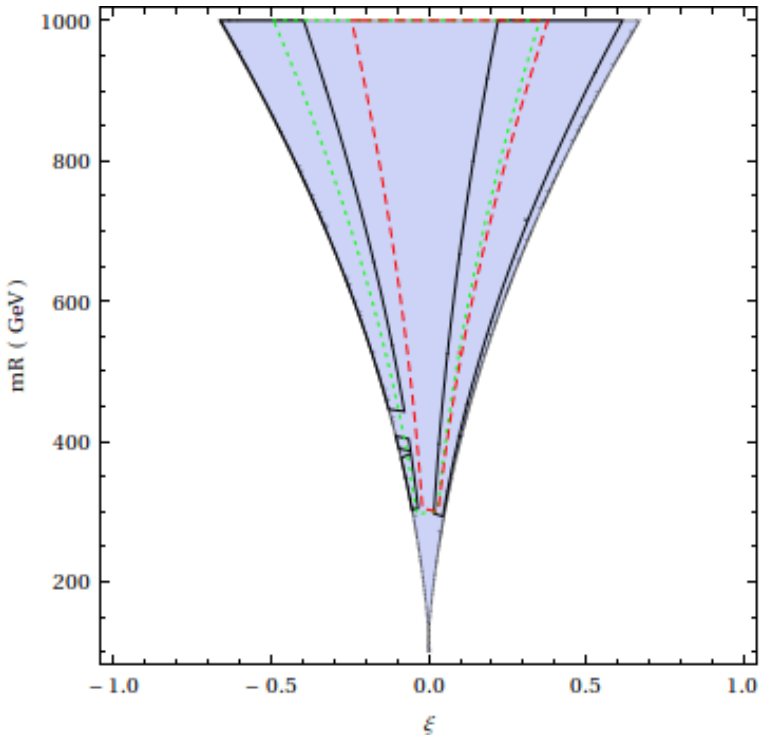
- Use most recent (post-*Moriond*) public results
- Observations: signal normalised to SM expectation, μ:

$$\mu_X = \left(a|c_g|^2 + b|c_W|^2\right) \frac{\Gamma(h \to X)}{\Gamma^{SM}(h \to X)}$$

  for process-dependent a, b
- Combine ATLAS, CMS in simple fashion: weighted mean

	WW	ZZ	$\gamma\gamma$	$b\bar{b}$	$\tau^+\tau^-$
ATLAS	1.0 ± 0.3	1.5 ± 0.4	1.6 ± 0.3	-0.4 ± 1.0	0.8 ± 0.7
CMS	0.68 ± 0.2	0.92 ± 0.21	0.77 ± 0.27	1.15 ± 0.62	1.1 ± 0.4
Average	0.78 ± 0.17	1.0 ± 0.2	1.1 ± 0.2	0.72 ± 0.53	1.0 ± 0.4

Higgs Constraints



- Shaded: theory allowed
- No constraints from $h \to f\bar{f}$
- Contours: 1-σ allowed regions
- On same scale, brane Higgs couplings identical to SM

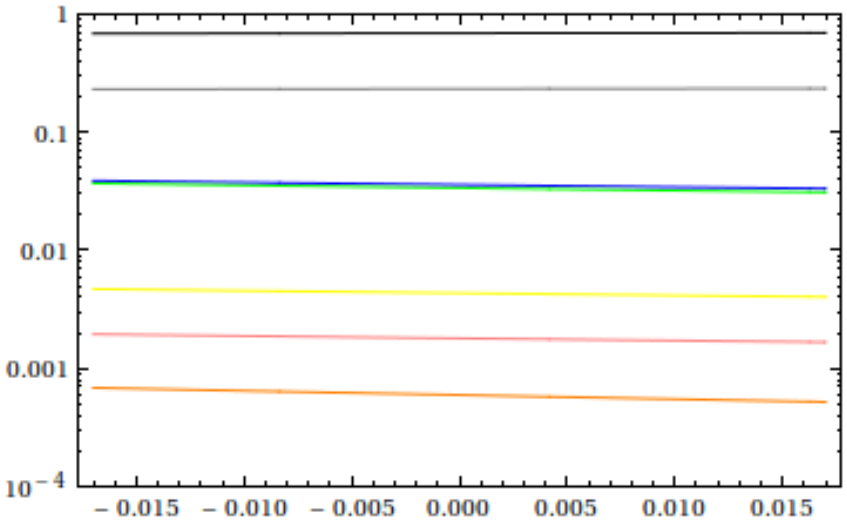
($\beta = 1, \Lambda_{IR} = 1$ TeV, $m_r = 500$ GeV)

Black: $h \to WW$; Green: ZZ; Red: $h \to \gamma\gamma$

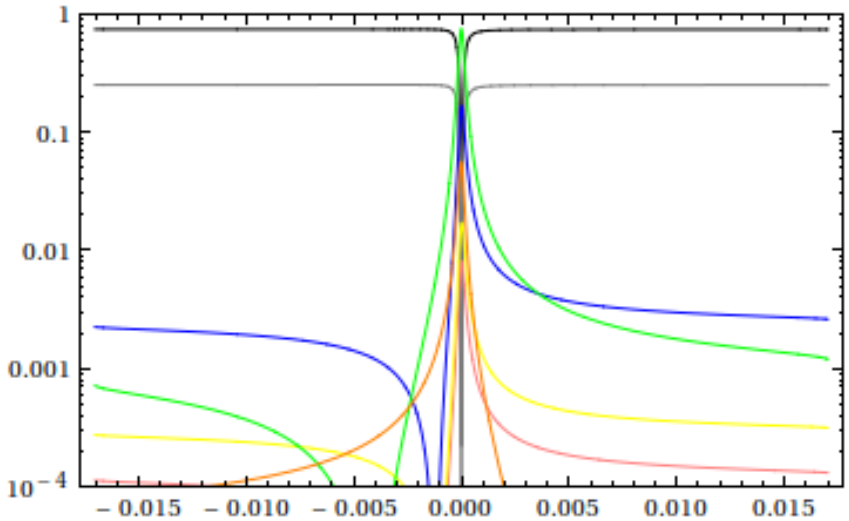
Radion Partial Widths

200 GeV

Brane Higgs:



Bulk Higgs:



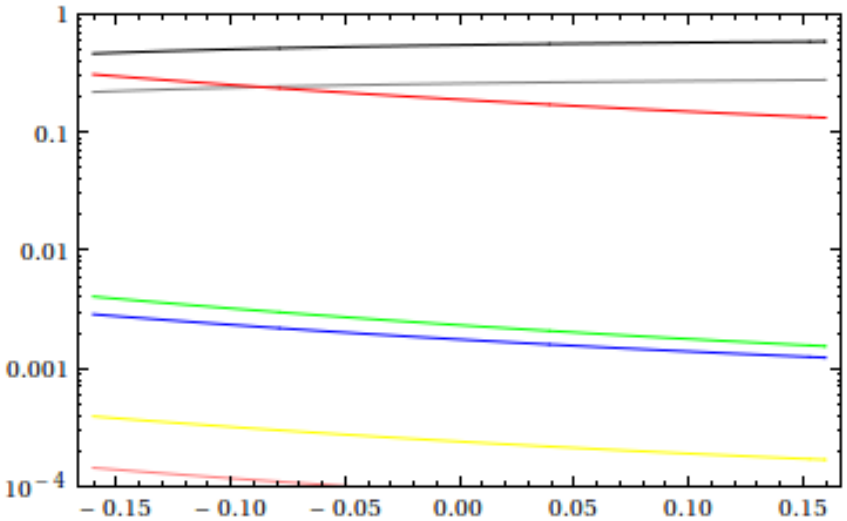
Black: W/Z; Blue: b; Yellow: τ; Green: g; Red: c; Orange: γ

Bulk Higgs suppresses width to WW, ZZ

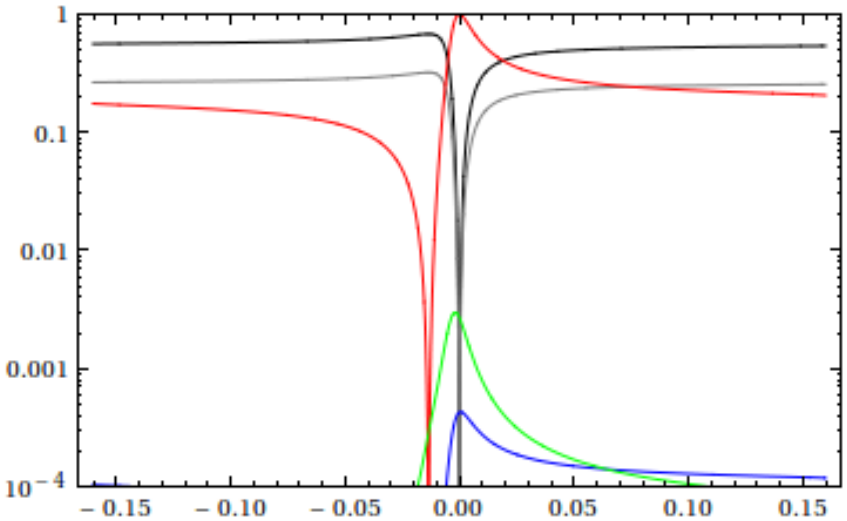
Radion Partial Widths

500 GeV

Brane Higgs:



Bulk Higgs:



Black: W/Z; Red: t; Blue: b; Yellow: τ; Green: g

Interesting $t\bar{t}$ signals?

Conclusions & Future Directions

1. Radion and bulk Higgs have both mass and kinetic mixing
2. Mass mixing dominates phenomenology, set by KK scale
3. Have used Higgs measurements to constrain mixing ξ
4. Have shown how radion couplings differ for bulk Higgs
5. To do: use LHC results to constrain radion parameter space