Radion Activated Higgs Mechanism

Ongoing work with Jay Hubisz and Gabriele Rigo

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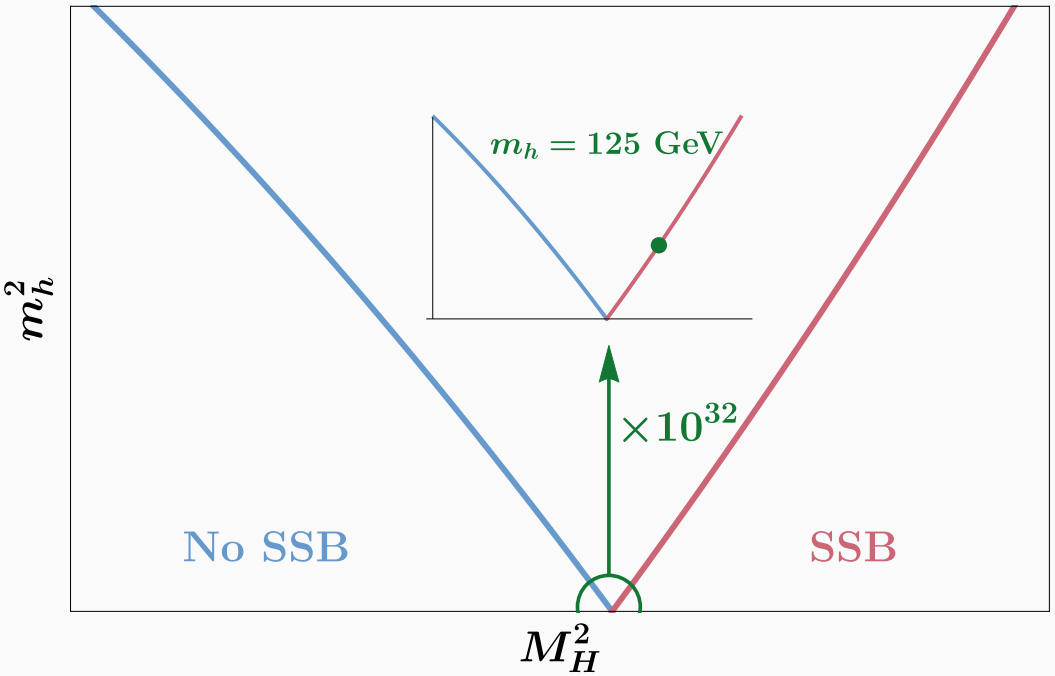
Fine Tuning Problem of the Higgs Mass

The Higgs mass is obtained from a potential defined at some high mass scale like M_{pl} or M_{GUT}, with a bare mass term.

$$V(|H|) = M_H^2|H|^2 + \lambda_H|H|^4 \quad , \quad m_h^2 \sim -M_H^2 + \Lambda^2$$



Standard Model seems to be very very close to the critical point unprotected by a symmetry.

Scalar Singlets and the Higgs

A scalar field Φ, which is a singlet under the SM, will couple to the Higgs doublet, since it is allowed by the symmetry.

$$\mathcal{L} \supset \lambda \Phi |H|^2$$

Such a coupling creates an effective dynamical mass term for the Higgs, which is a function of the singlet field.

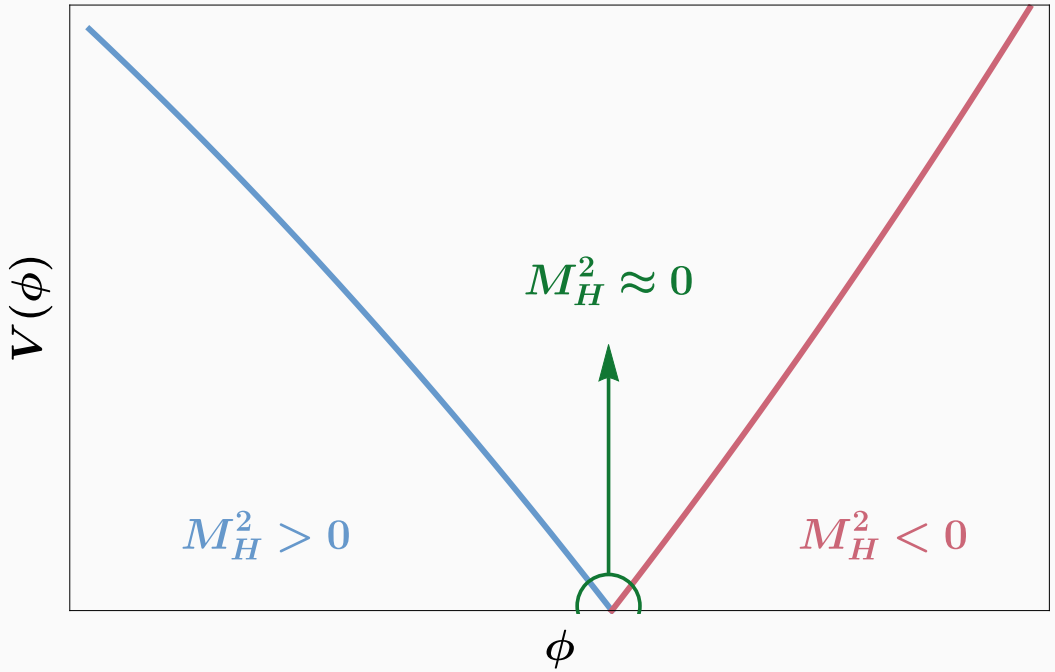
$$M_H^2 \to M_H^2(\Phi) = M_H^2 - \lambda \Phi$$

The potential responsible for electroweak symmetry breaking now depends on multiple fields.

$$V(|H|) \to V(|H|, \Phi) = \left(M_H^2 - \lambda \Phi\right) |H|^2 + \lambda_H |H|^4 + V(\Phi)$$

A Naturally Light Higgs from Scalar Singlets

The minimum of the multi-scalar potential might lie on a region close to the Higgs critical surface and provide an attempt to explain the Higgs criticality in the Standard Model.



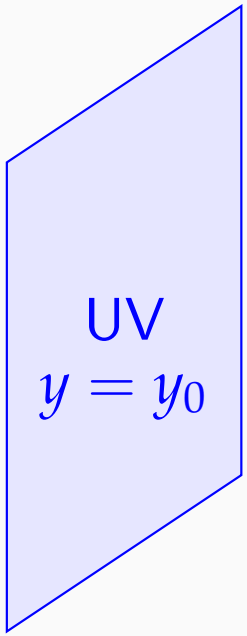
Such a property can lead to non-perturbative, violent cosmological dynamics which can have novel experimental signatures. Amin, Fan, Lozanov, Reece 1802.00444

What are we aiming for?

1. Engineer models where the minimum of a modulus field coincides with a light Higgs.
2. What are the ingredients for such models?
3. What kind of fine tuning (if any) is needed to realize such models?

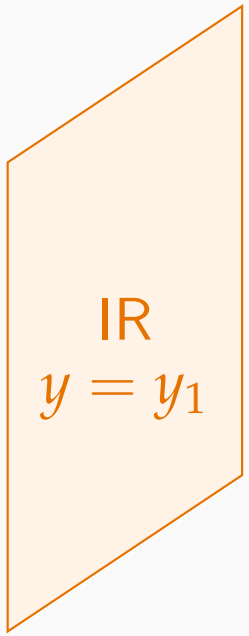
Warped Extra Dimensions and the Radion

A classical gravity theory on AdS_5 space bounded by UV and IR 3-branes. L. Randall and R. Sundrum hep-ph/9905221



$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}\,dx^\mu\,dx^\nu - dy^2$$

brane separation $\Leftrightarrow$ radion VEV



The mass scales on the IR brane are suppressed with respect to the mass scales on the UV brane.

$$\frac{\Lambda_{\text{IR}}}{\Lambda_{\text{UV}}} \sim \frac{e^{-ky_1}}{e^{-ky_0}} \ll 1 \quad \text{for} \quad y_1 - y_0 \sim \mathcal{O}(20)$$

Strongly Coupled Theories and the Dilaton

The AdS/CFT correspondance provides a relation between warped extra dimensions and strongly coupled field theories which are conformal over a large energy scale.

AdS_5 with UV brane at $e^{ky_0} = \Lambda_{\text{UV}} \Leftrightarrow \mathcal{L}_{\text{4D-CFT}}$ with cutoff at Λ_{UV}

IR brane at $e^{ky_1} = \Lambda_{\text{IR}} \Leftrightarrow$ Confinement at $\Lambda_{\text{IR}} \ll \Lambda_{\text{UV}}$

Movement in $+y$ direction $\Leftrightarrow$ RG running to lower energies

Radion $\Leftrightarrow$ Dilaton as (p)NGB of ~~CFT~~

Effective Potential and Moduli Stabilization

Integrate out the extra dimension to get a 4D effective potential.

$$V_{\text{eff}}(f) = \underbrace{\left(T_0 - \frac{6k}{\kappa^2}\right)}_{\equiv 0 \Rightarrow \text{CC tuning}} + \underbrace{e^{-4k(y_1-y_0)}}_{\left(\frac{f}{k}\right)^4}\left(T_1 + \frac{6k}{\kappa^2}\right) \Rightarrow \text{No min wrt } f$$

To stabilize the modulus, i.e. get a min for f we need to add scalar fields to the bulk. W. D. Goldberger and M. B. Wise hep-ph/9907447

$$\mathrm{d}s^2 = e^{-2k|y|}\eta_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu - G(y)^{-1}\,\mathrm{d}y^2\,, \quad G(y) \Rightarrow \cancel{\text{AdS}_5}$$

A minimum at small f can be generated for $\epsilon \sim \mathcal{O}(0.1)$ bulk scalar mass $\Rightarrow$ mild explicit breaking of CFT by $[\mathcal{O}_\epsilon] = 4 - \epsilon$ operator.

$$V_{\text{eff}}(f) \sim \lambda_\epsilon k^\epsilon f^{4-\epsilon} + \lambda_4 f^4 \Rightarrow \text{radion/dilaton as pNGB of } \cancel{\text{CFT}}$$

Suppressing the Electroweak Scale

Observations imply $f \gtrsim \mathcal{O}(\text{TeV})$. Still need to suppress the electroweak scale.

$$\frac{v_{\text{EW}}}{f} \lesssim \mathcal{O}(0.1) \Rightarrow \text{Little Hierarchy Problem}$$

Radion/dilaton Φ is a scalar singlet, so it couples to Higgs.

$$\mathcal{L} \supset \lambda_\Phi \Phi |H|^2.$$

Can the combined Higgs/Radion potential solve the little hierarchy problem?

The General Model

The general action we consider is

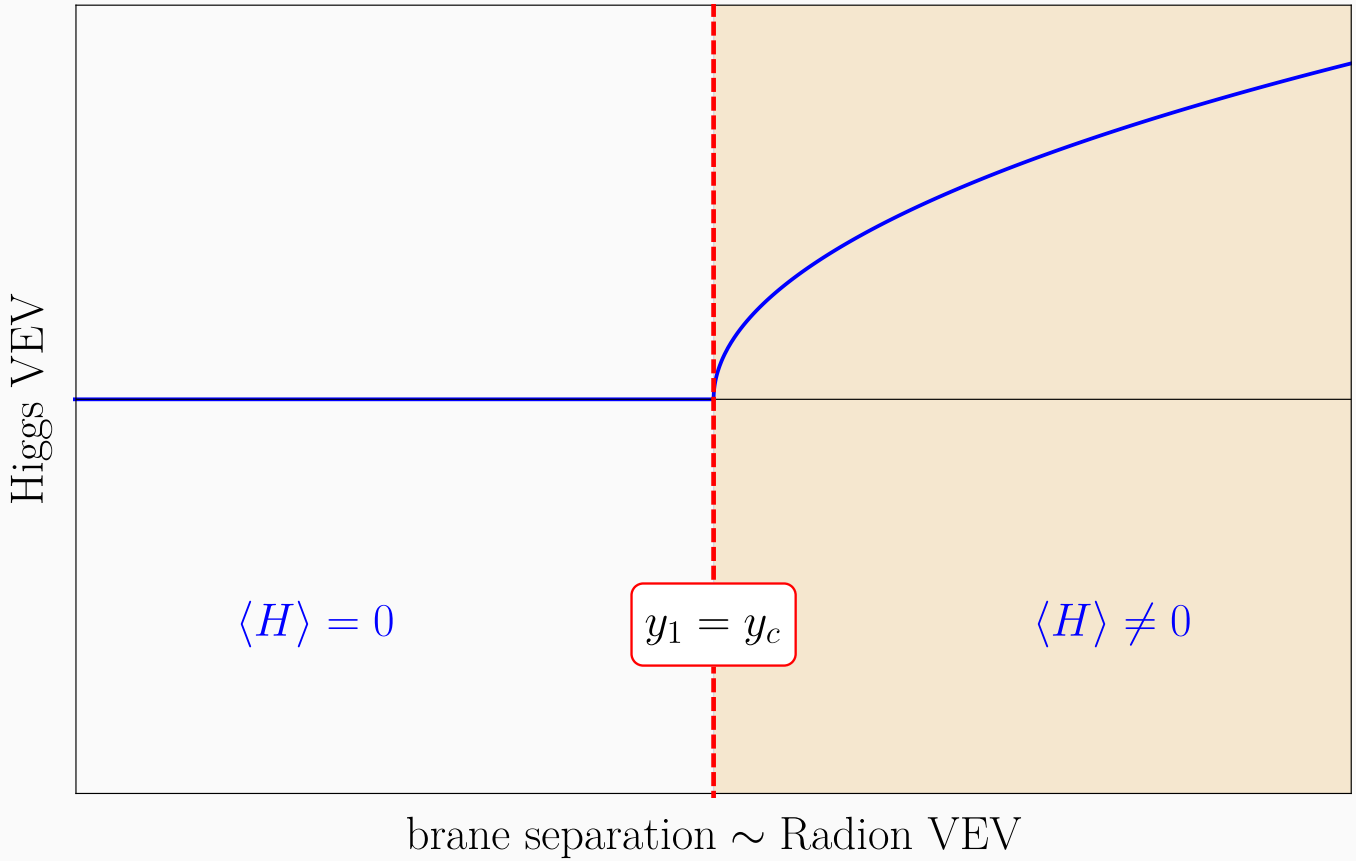
$$S = \int \mathrm{d}^5x\,\sqrt{g}\left[\frac{1}{2}\sum_i (\partial\phi_i)^2 + \frac{6k}{\kappa^2} - V_B(\{\phi\}) - \frac{\mathcal{R}}{2\kappa^2}\right]$$
$$- \int \mathrm{d}^4x\,\sqrt{-g_0}V_0(\{\phi\})\Big|_{y=y_0} - \int \mathrm{d}^4x\,\sqrt{-g_1}V_1(\{\phi\})\Big|_{y=y_1}$$

After integrating out the extra dimension, the effective potential will depend on both the radion VEV and the Higgs VEV.

$$V_{\text{eff}}(f,|H|) = \left[V_0(f,|H|) - \frac{6k}{\kappa^2}\sqrt{G(f,|H|)}\right]\Big|_{y=y_0}$$
$$+ \left(\frac{f}{k}\right)^4\left[V_1(f,|H|) + \frac{6k}{\kappa^2}\sqrt{G(f,|H|)}\right]\Big|_{y=y_1}$$

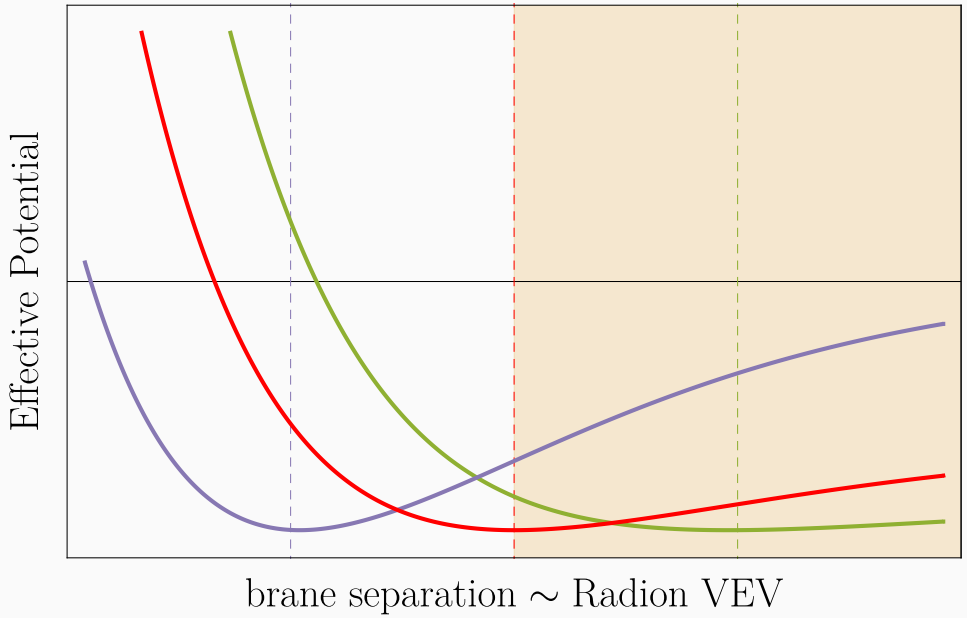
Radion Activated Symmetry Breaking

We are interested in models where the electroweak criticality is a function of the brane separation, i.e. where the radion activates EW symmetry breaking.



Tuning the Brane Tension to get a Light Higgs

In the absence of Higgs VEV, T_1 sets y_{min} at which the effective potential is minimized.



There exists a critical T_1^{crit} which make y_{min} coincide with the Higgs criticality. $T_1 = T_1^{\text{crit}} \Rightarrow y_{\text{min}} = y_c$

How much T_1-tuning we need to get $v_{\text{EW}}/f \lesssim \mathcal{O}(0.1)$?

Example Models

To calculate tuning quantitatively, we need specific models.

- **Model #1: Higgs on the IR brane:** A GW field ϕ in the bulk, coupled to the Higgs on the IR brane.

$$V_B = \frac{1}{2}\epsilon(4-\epsilon)\phi^2 \quad \Leftrightarrow \quad [\mathcal{O}_\epsilon] = 4-\epsilon$$

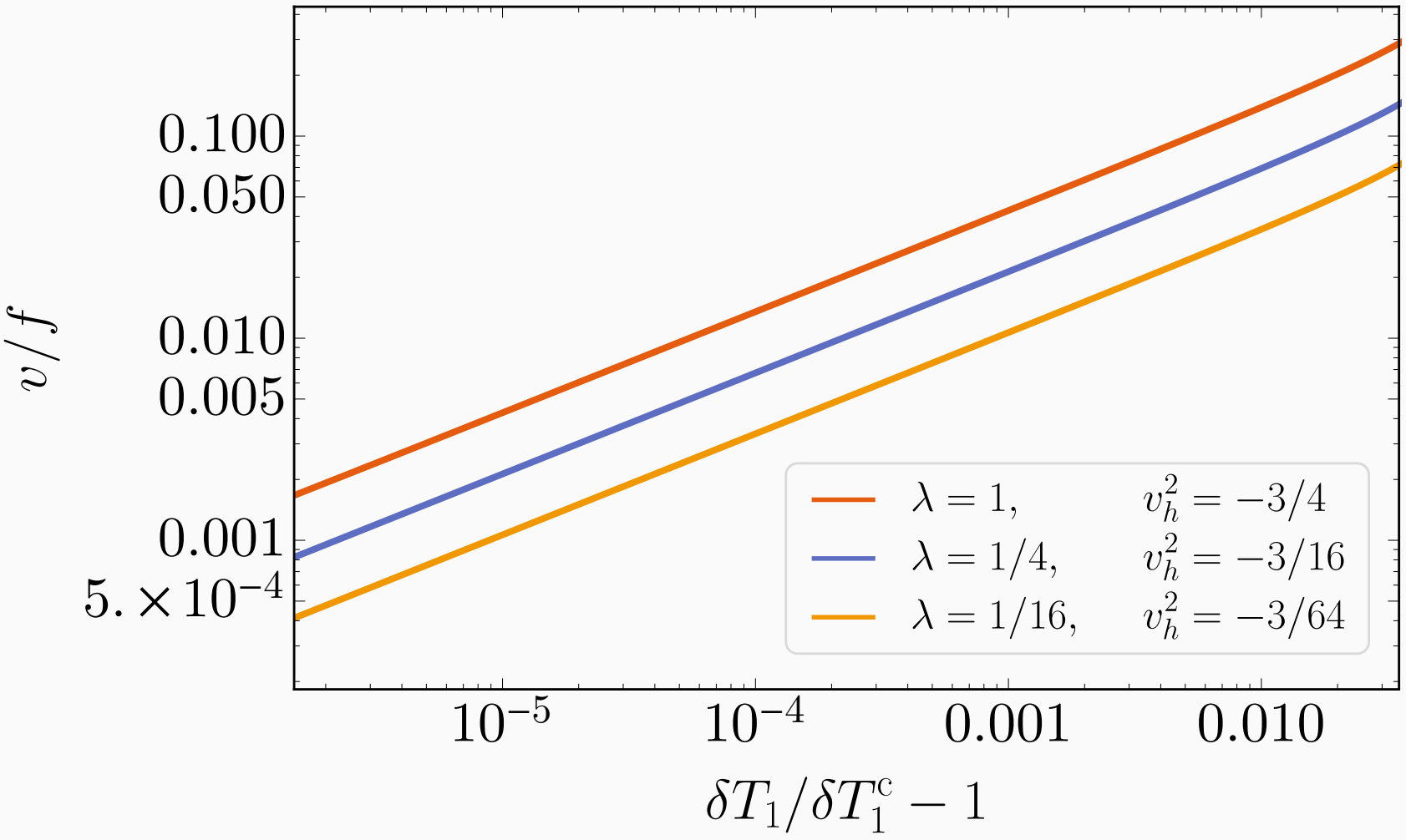
$$V_1 = T_1 + \gamma_1 \left(\phi - v_1\right)^2 + \lambda_H |H|^2 \left(|H|^2 - v_H^2 - \lambda\phi\right) |H|^2$$

- **Model #2: Higgs in the bulk:** Both the GW field ϕ and the Higgs live in the bulk and coupled to each other only through gravity.

$$V_B = \frac{1}{2}\epsilon(4-\epsilon)\phi^2 + \left(-4+\nu^2\right)|H|^2 \quad \Leftrightarrow \quad [\mathcal{O}_H^\dagger \mathcal{O}_H] = 4-\nu^2$$

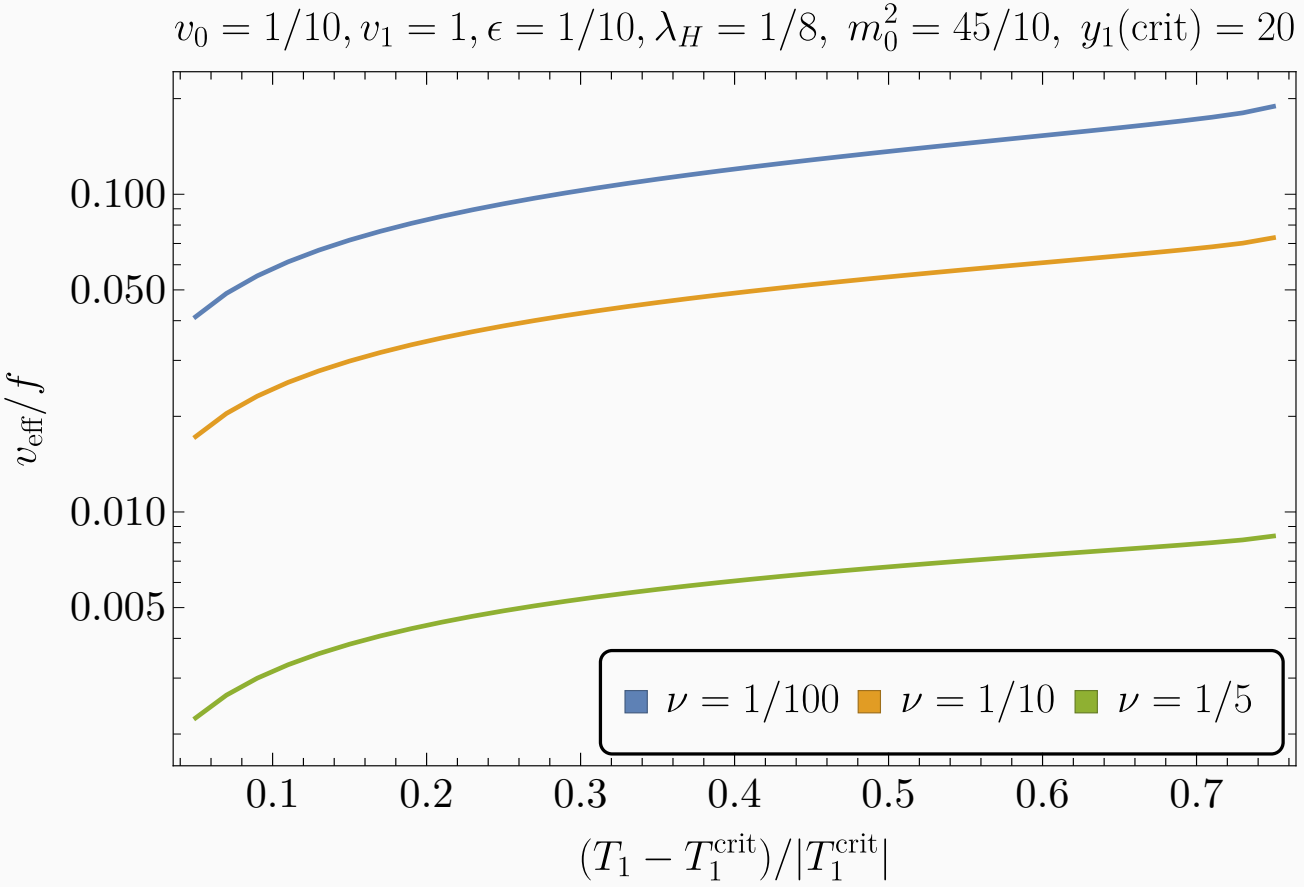
$$V_1 = T_1 + \gamma_1 \left(\phi - v_1\right)^2 + \lambda_H |H|^2 \left(|H|^2 - v_H^2\right) |H|^2$$

Example Model #1: Higgs on the brane



$\mathcal{O}(0.1)$ suppression of electroweak scale $v_{\rm EW}$ wrt KK scale f can be obtained at the price of $\mathcal{O}(0.01)$ tuning T_1.

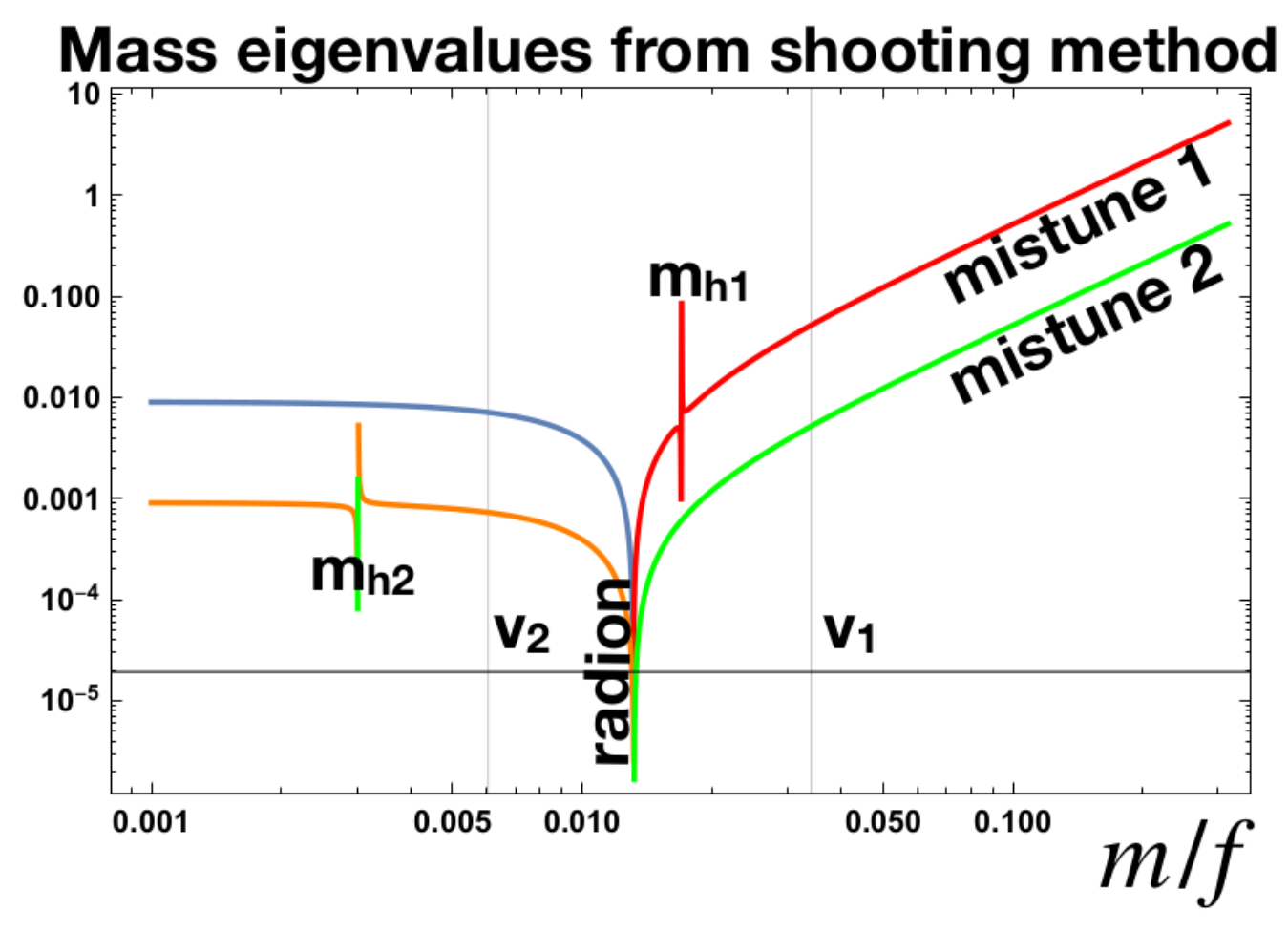
Example Model #2: Higgs in the bulk (Preliminary)



Naively it looks like $\mathcal{O}(0.01)$ suppression can be obtained with a mild tuning, y_c is very sensitive to the IR brane mass for the Higgs.

$$\frac{\lambda_H v_H^2(y_c = 20) - \lambda_H v_H^2(y_c = 30)}{\lambda_H v_H^2(y_c = 20)} \approx 0.002$$

Mass Spectrum for the Higgs on the Brane



It is possible to make the Higgs lighter than the radion. Getting the mass spectrum for the Higgs in the bulk is a work in progress.

Conclusion and Outlook

We have explored the interplay between the radius stabilization and the Higgs mechanism in RS models.

At the price of (fine/mild) tuning, such an interplay can suppress the EW scale v_{EW} wrt KK (or CFT breaking) scale f.

The main ingredient for such models is that the EW symmetry breaking occurs at particular points of the moduli space.

A partial to-do list:

- More realistic models: (Composite $\Leftrightarrow A_5$) Higgs.
- Models where the suppression occurs over a large range of parameter space, i.e. less tuning.
- Cosmology: Brane dynamics, rolling radion, ...