# Bulk Higgs in Warped Extra Dimensions

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Based on work with J. A. Cabrer and G. v. Gersdorff:
arXiv:0907.5361; arXiv:1011.2205; arXiv:1103.1388;
arXiv:1104.3149; arXiv:1104.5253;+ in preparation

# Outline

The outline of this talk is

**Outline**

- Introduction
- General results
- RS model
- Our model
- Flavor violation (preliminary)
- Conclusion

# Introduction

- The SM of EW interactions suffers from a naturalness problem as the Higgs mass is sensitive to UV cutoff $\Lambda$
- This is the

**Hierarchy (Naturalness) Problem**

- A number of SM extensions have been proposed with the aim of solving the hierarchy problem
- One of the most interesting solutions (warped models) were originally proposed by Randall and Sundrum (RS) [1] based on an extra dimension with AdS metric

**AdS metric**

$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2, \quad A(y) = ky$$

and UV and IR boundaries located at $y = 0$ and $y = y_1$

[1] L. Randall and R. Sundrum, arXiv:hep-ph/9905221

- The original model had all the SM localized on the IR boundary and the Planckian Higgs mass redshifted to the TeV scale by the warp factor
- Now the SM is not necessarily localized at the IR boundary
  - If fermions (and gauge bosons) propagate in the bulk with $\mathcal{O}(k)$ Dirac masses the model could provide a theory of flavor
  - If the Higgs propagate in the bulk it can solve the hierarchy problem provided that it is "sufficiently localized" towards the IR boundary
- However confronting the model with

**Electroweak Precision Tests (EWPT)**

Implies strong bounds on the KK modes

- $m_{KK} \gtrsim 13$ TeV (for localized Higgs)
- No hope for LHC searches
- Re-creating a little hierarchy problem

- The origin of the previous bound is the large volume compactification and the behavior of the $T$ parameter

$$\alpha T \sim k y_1$$

- Some solutions to this problem have been proposed
  - To enlarge the 5D model to incorporate a gauge custodial (bulk) symmetry [2] (extension of 5D SM)
  - To introduce a large IR brane kinetic terms [3] (relies on unknown UV physics)
  - To generalize the AdS metric in the IR with a strong deformation of conformality such that the coupling of EW KK modes to the Higgs is suppressed [4]
- We will consider here the last solution
- We will present results for general metrics, Higgs and fermion profiles

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[2] K. Agashe et al., arXiv:hep-ph/0308036

[3] M. Carena et al., arXiv:hep-ph/0212307

[4] J. Cabrer et al., arXiv:1011.2205

# General results

- We will then consider the SM propagating in a 5D space with an arbitrary metric $A(y)$
- 5D gauge fields $g_M(x,y)$, $W^i_M(x,y)$ and $B_M(x,y)$ propagating in the bulk
- A stabilizing field $\phi(x,y)$ fixing the value of $A(y_1)$

**A bulk SM Higgs**

$$H(x,y) = \frac{1}{\sqrt{2}} e^{i\chi(x,y)} \begin{pmatrix} 0 \\ h(y) + \xi(x,y) \end{pmatrix}$$

- $\chi(x,y)$ contains the 4D Goldstone bosons
- $h(y)$ is the 5D Higgs background
- $\xi(x,y)$ describes the Higgs fluctuations

- We will consider for the moment an arbitrary background $h(y)$

## The effective SM-like Lagrangian for the Higgs

$$\mathcal{L}_{\rm eff} = -|D_\mu \mathcal{H}|^2 + \mu^2|\mathcal{H}|^2 - \lambda|\mathcal{H}|^4$$
$$\mu^2 \sim Z^{-1}\rho^2\,, \qquad \lambda \sim Z^{-2}$$

- The IR scale $\rho$ and dimensionless quantity $Z$ are

## $Z$ is Higgs wave function renormalization

$$\rho = k e^{-A(y_1)}\,, \qquad Z = k\int_0^{y_1} dy\, \frac{h^2(y)}{h^2(y_1)} e^{-2A(y)+2A(y_1)}$$

- The physical Higgs mass is $m_H^2 = 2\mu^2 \sim 2Z^{-1}\rho^2$
- Radiative corrections in the effective theory below the scale $\Lambda \sim m_{KK}$ will tend to destabilize light Higgs masses: some degree of fine-tuning is needed to not spoil EWSB and to keep the Higgs light

# UNIVERSAL ELECTROWEAK OBSERVABLES

- Universal electroweak precision observables are commonly mapped to the set $(T, S, W, Y)$ [5]
- They are defined as

**Oblique observables**

$$\alpha T = m_W^{-2}\left[c_W^2 \Pi_Z(0) - \Pi_W(0)\right]$$

$$\alpha S = 4 s_W^2 c_W^2 \left[\Pi'_Z(0) - \Pi'_\gamma(0)\right]$$

$$2 m_W^{-2} Y = s_W^2 \Pi''_Z(0) + c_W^2 \Pi''_\gamma(0)$$

$$2 m_W^{-2} W = c_W^2 \Pi''_Z(0) + s_W^2 \Pi''_\gamma(0)$$

- Associated with the coefficients of

**Effective operators (d=6)**

$$|H^\dagger D_\mu H|^2\,, \quad H^\dagger W_{\mu\nu} H B^{\mu\nu}\,, \quad (\partial_\rho B_{\mu\nu})^2\,, \quad (D_\rho W_{\mu\nu})^2$$

[5] R. Barbieri et al. hep-ph/0405040

- These observables can be computed as

**Oblique observables**

$$\alpha T = s_W^2 m_Z^2 \frac{I_2}{\rho^2}\frac{ky_1}{Z^2}$$

$$\alpha S = 8 s_W^2 c_W^2 m_Z^2 \frac{I_1}{\rho^2}\frac{1}{Z}$$

$$Y = W = c_W^2 m_Z^2 \frac{I_0}{\rho^2}\frac{1}{ky_1}$$

- where

$$I_n = k^3 \int_0^{y_1} (y_1 - y)^{2-n} u^n(y) e^{2A(y)-2A(y_1)}$$

$$I_n/\rho^2 = \mathcal{O}(1/m_{KK}^2)$$

- $T$ is volume enhanced and $Z^2$ suppressed
- $S$ is $Z$ suppressed and $W = Y$ is volume suppressed

# FERMION MASSES (PRELIMINARY)





- Consider the fermion action [6]

$$S = \int dy\, e^{-3A} \left(i\bar{\psi}_L \partial\!\!\!/ \psi_L + i\bar{\psi}_R \partial\!\!\!/ \psi_R\right)$$
$$+ e^{-4A} \left(\bar{\psi}_R \psi_L' - 2A' \bar{\psi}_R \psi_L - M(y)\bar{\psi}_R \psi_L + \text{h.c.}\right)$$

- There is a zero mode with profile

$$\psi_{L,R} = e^{2A(y) - Q(y)_{L,R}}\,, \qquad \psi_{R,L} \equiv 0$$

where $Q(y)_{R,L} = \pm \int_0^y M(y')$

- We can make the choice $Q_f(y) = c_f A(y)$ which coincides with that used in RS models where $Q_f^{RS} = c_f ky$

[6] J. Cabrer, G. Gersdorff, M.Q., in preparation

- A very useful quantity is

$$\Omega_f(y) = \frac{U_f(y)}{U_f(y_1)}\,, \quad U_f(y) = \int_0^y \exp\left[(1-2c_f)A(y')\right]$$

- The 4D Yukawa couplings for quarks are given by

$$Y_{ij}^q = \hat{Y}_{ij}^q \; F(c_{Q_L^i}, c_{q_R^j})\,, \qquad q = u,\, d$$

$$F(c_1, c_2) = \frac{\int h(y) e^{-(c_1+c_2)A(y)}}{\left[\int h^2(y) e^{-2A} \int e^{(1-2c_1)A} \int e^{(1-2c_2)A}\right]^{\frac{1}{2}}}$$

- Here $\hat{Y}$ is the 5D Yukawa coupling with mass dimension $-\frac{1}{2}$
- If flavor is explained by different localization in the extra dimension there is flavor violation mainly from KK gluons

# Flavor violation (preliminary)

- The dominant flavor violation comes from the KK gluons
- We parametrize the most constraining

## $\Delta F = 2$ Lagrangian

$$\mathcal{H}_{sd}^{\Delta F=2} = -C_1^{sd}(\bar{s}_L\gamma^\mu d_L)^2 - \tilde{C}_1^{sd}(\bar{s}_R\gamma^\mu d_R)^2 + C_4^{sd}(\bar{s}_L d_R)(\bar{s}_R d_L)$$

- With

## Wilson coefficients

$$C_1^{sd} = \frac{g_s^2\, y_1}{6}\int e^{2A}(\Omega_{d_L}^{21})^2$$

$$\tilde{C}_1^{sd} = \frac{g_s^2\, y_1}{6}\int e^{2A}(\Omega_{d_R}^{21})^2$$

$$C_4^{sd} = -g_s^2\, y_1\int e^{2A}\Omega_{d_L}^{21}\Omega_{d_R}^{21}$$

- Where [7]

$$\Omega^{ij}_{q_\chi}=(V_{q_\chi}\Omega^{diag}_{q_\chi}V^\dagger_{q_\chi})^{ij}\qquad \chi=L,R\quad q=u,d$$

- Using

### Unitarity of transformations

$$\Omega^{21}_{d_L}=(\Omega^2_{d_L}-\Omega^1_{d_L})V^{22}_{d_L}V^{*12}_{d_L}+(\Omega^3_{d_L}-\Omega^1_{d_L})V^{23}_{d_L}V^{*13}_{d_L}$$

- and similarly for $L\to R$

[7] J. Cabrer, G. Gersdorff, M.Q., in preparation

# RS MODEL

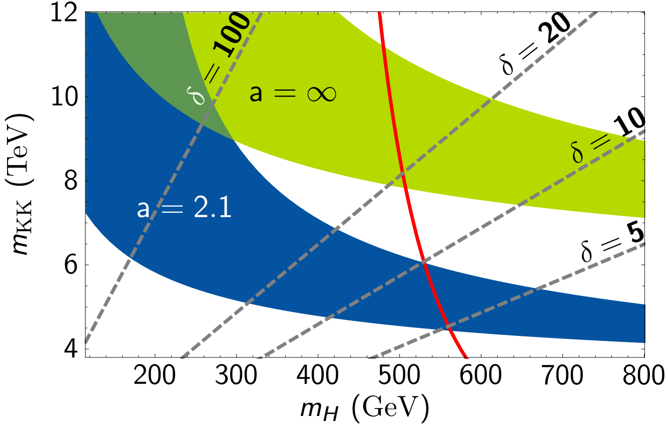
- In the RS model one introduces a 5D bulk Higgs mass: $M^2 = a(a-4)k^2$
- Holographic interpretation $a = \dim(\mathcal{O}_H)$
- Solution to the EOM: $h(y) \propto e^{aky}$
- No fine-tuning for $a > 2$: hierarchy solved with a composite Higgs
- $Z = \frac{1}{2(a-1)} < 1/2$ provides no suppression $\Rightarrow$ large $m_{KK}$ & heavy Higgs & 5D Higgs as IR delocalized as possible
- For instance for $m_H = 150$ GeV the 95% CL bound is

**For localized 5D Higgs: $a \to \infty$**

$$m_{KK} \gtrsim 12.5 \text{ TeV}$$

**For delocalized 5D Higgs: $a = 2.1$**

$$m_{KK} \gtrsim 7 \text{ TeV}$$




*95% CL regions in the $(m_H, m_{KK})$ plane for RS and the cases of a localized and a bulk Higgs with $a = 2.1$. Solid line is the perturbativity bound $\beta_\lambda^{(2)} = 0.5\ \beta_\lambda^{(1)}$*

# Our model

- We will consider a model with a conformal deformation in the IR
- It contains a stabilizing field $\phi$ which leads to

**The metric**

$$A(y) = ky - \frac{1}{\nu^2}\log\left(1 - y/(y_1 + \Delta)\right), \quad \nu \in \mathbb{R}$$

- The metric has a spurious singularity located at $y_s = y_1 + \Delta$ outside the physical interval
- The dynamics of $\phi$ fixes $y_1$ $[A(y_1)]$ and $\Delta$ as in GW
- A 5D bulk Higgs mass: $M^2(\phi) = k^2[a(a-4) - be^{\nu\phi}]$ where $a$ and $b$ are arbitrary constants
- $b$ can be absorbed by a shift of $\phi_0$ at the UV: we fix it to $b = 1$

- The holographic interpretation of $a$ is now a bit different from RS

**In the IR**

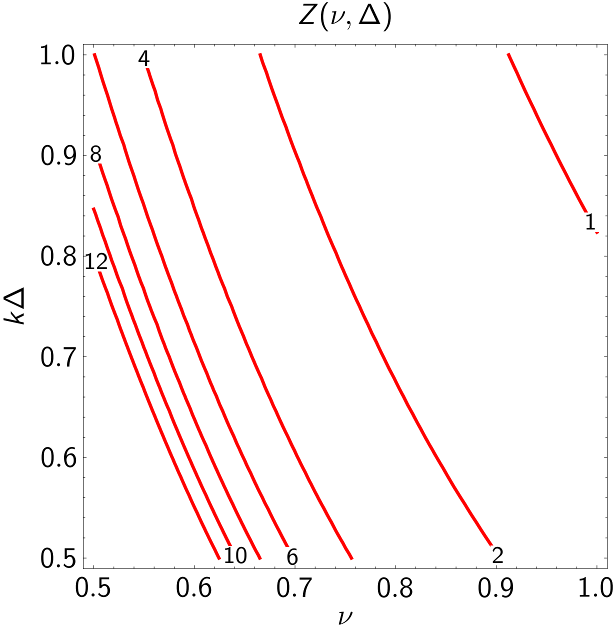
$$\dim(\mathcal{O}_H)^{IR} = \frac{a}{1 + \frac{1}{k\Delta\nu^2}}$$

- The solution to the EOM $h(y) = c_1 e^{aky} + c_2 \int^y e^{4A(y')-2aky'}$ imposes the constraint

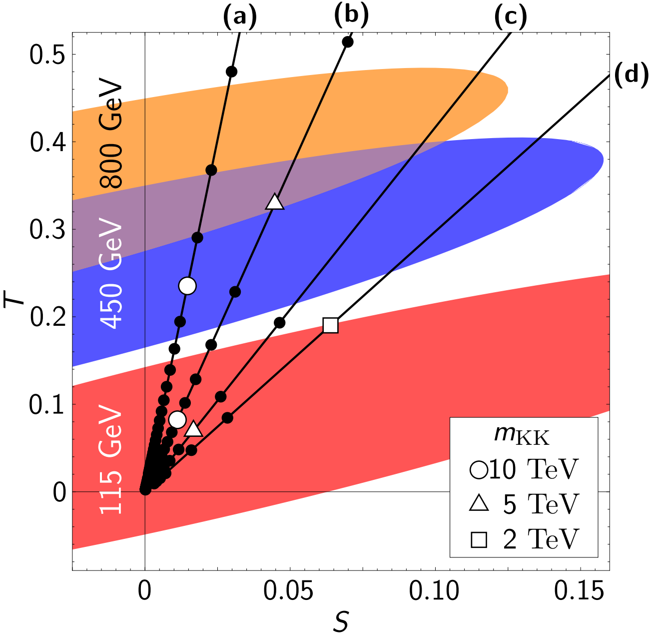
**Hierarchy condition ($a > 2$ for RS)**

$$a \gtrsim a_0 = 2A_1/ky_1$$

- In many cases $Z \gg 1$ which softens the bounds on EWPO




*Contour lines of fixed* $Z(\nu,\Delta)$ *where* $a = a_0(\nu,\Delta)$ *and* $A(y_1) = 35$




95% CL regions. Ray (c) [(d)] is our model with $k\Delta = 1$ and $\nu = 0.7$ [$\nu = 0.6$]

- For instance for $m_H = 150$ GeV and $a = a_0$ the 95% CL bound is

**For $k\Delta = 1$, $\nu = 0.7$**

$$m_{KK} \gtrsim 3\ \mathrm{TeV}$$

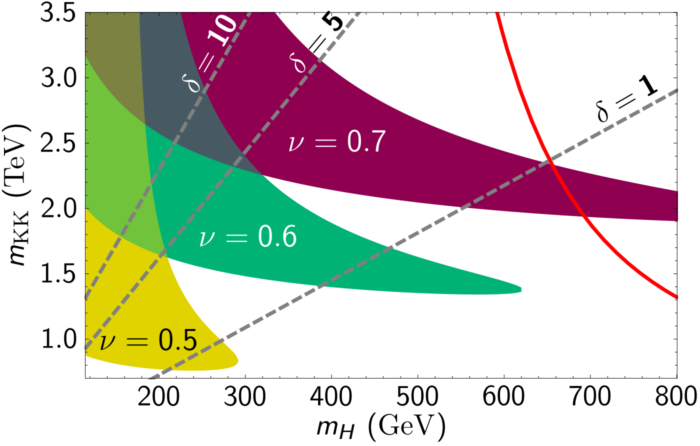
**For $k\Delta = 1$, $\nu = 0.6$**

$$m_{KK} \gtrsim 2\ \mathrm{TeV}$$

This shows that :

  - A light or heavy Higgs can be consistent with KK-modes accessible at LHC energies
  - The measurement of the Higgs mass at LHC should constrain the model parameters

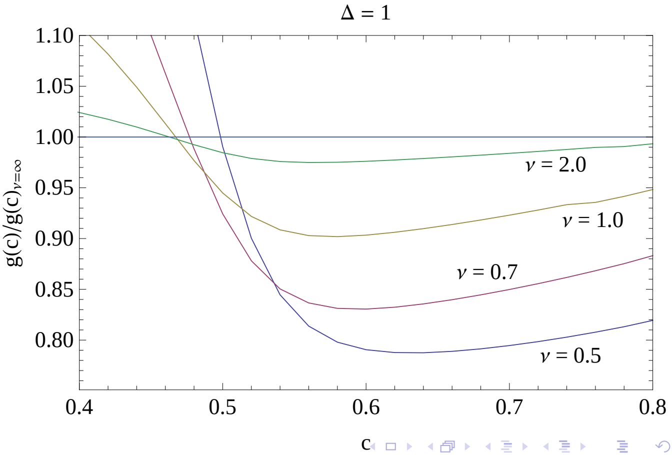
- These two features are exhibited in the next plot




*95% CL regions in the $(m_H, m_{KK})$ plane for our model with $k\Delta = 1$ and $\nu = 0.7, 0.6, 0.5$. Solid line corresponds to the perturbativity bound $\beta_\lambda^{(2)} = 0.5\ \beta_\lambda^{(1)}$*

# Flavor violation (preliminary)

- The nine 5D quark masses $c_{Q_L^i}, c_{u_R^i}, c_{d_R^i}$: adjusted to satisfy the quark mass and CKM matrix relations
- Dominant flavor violation comes from the KK gluons
- The general trend on the coupling of KK gluons to fermions in our model as compared to the RS model



- To quantify the improvement that we can achieve within our model, we have randomly generated complex 5D Yukawa couplings and performed a $\chi^2$ fit to the nine parameters $c_f$
- We have considered both RS and our model with $\nu = 0.5, \ \Delta = 1/k$
- Each set of 5D Yukawas thus gives rise to two sets of $c_f$, one for RS and one for our model.
- The $c_f$ for our model are consistently larger than in RS, giving rise to reduced and more universal couplings
- With these data points we then compute the exact mixing matrices numerically and use them to find the coefficients $C_i$: in particular

$$|\mathrm{Im}\; C_4^{sd}| \lesssim 2.6 \times 10^{-17} \ \mathrm{GeV}^{-2} \ 95\% \ C.L.$$

which is the most constrained one from data
- These are then translated into bounds on $m_{KK}$

- We have considered 2,000 randomly chosen 5D Yukawas with $1 < \sqrt{k}|\hat{Y}^q_{ij}| < 2$

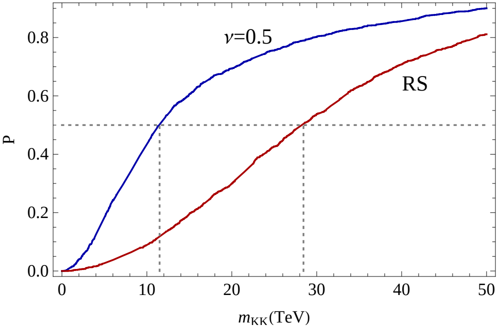



Figure: *Cumulative distribution function of the bounds in the cases of RS (red line) and our model (blue line). We also show the median of the two distributions (dashed lines)*

- For the same distribution [8]

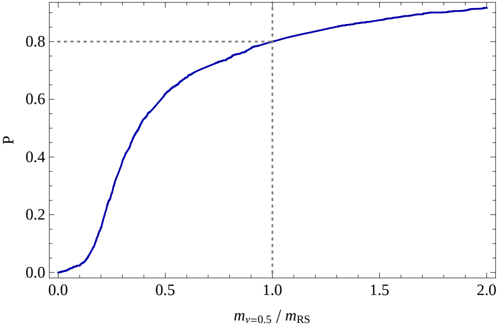



Figure: *Cumulative distribution function of the bounds ratio* $m_{KK}^{\nu=0.5}/m_{KK}^{RS}$

- We obtain a probability (percentile) 80% (50% median) for

$$m_{KK}^{\nu=0.5} < m_{KK}^{RS} \; (m_{KK}^{\nu=0.5} < 0.4 m_{KK}^{RS})$$

[8] J. Cabrer, G. Gersdorff, M.Q., in preparation

# Conclusions

- We have considered models where the 5D SM gauge and Higgs bosons propagate in the bulk
- In the RS model a heavy Higgs is more natural than a light one for which there is a "little hierarchy problem"

**RS (non-custodial) bound for $m_H = 115$ GeV**

$$(S, T, W, Y) \Rightarrow m_{KK} \gtrsim 7 \text{ TeV @ } 95\% \; CL$$

- In the model with an IR deformation the KK spectrum can be accessible to LHC both for light and heavy Higgs

**Our model with $k\Delta = 1$ and $\nu = 0.6$ for $m_H = 115$ GeV**

$$(S, T, W, Y) \Rightarrow m_{KK} \gtrsim 2 \text{ TeV @ } 95\% \; CL$$

- Higgs discovery at LHC will constrain the parameters!

- If fermions are conveniently localized toward the fifth dimension a

  - Theory of Flavor

  can be constructed
- The $c_f$ for our model are consistently larger than in RS, giving rise to reduced and more universal couplings

  - Flavor Violation

  appears dominantly from KK gluons
- A random choice of 5D Yukawas also leads to improvement in our model with respect to RS
- We are at present implementing other observables $Zb\bar{b}$, $C_1, \ldots$ in our model [9]

[9] J. Cabrer, G. Gersdorf, M.Q., in preparation;
A. Carmona, E. Ponton, J. Santiago, arXiv:1107.1500