The Phenomenology of Models with Warped Extra Dimensions and a Bulk Higgs.

Paul Archer
archer@uni-mainz.de

In collaboration with
Marcela Carena, Adrian Carmona & Matthias Neubert

Snowmass on the Pacific
29th - 31st May

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Why study a Bulk Higgs?

- **Offers concrete model for investigating the effect of changing the scaling dimension of the Higgs operator.**
- Has appealing description of Fermion Mass Hierarchy (Agashe, Okui & Sundrum '08, PRA '12, v. Gersdorff, Quiros, Weichers '12)
- In Randall and Sundrum model, no 'bottom up' reason for Higgs to have special status as only brane localised field.
- Reduces electroweak (EW) and flavour constraints relative to brane localised Higgs.
- ...

Why study a Bulk Higgs?

- **Offers concrete model for investigating the effect of changing the scaling dimension of the Higgs operator.**
- Has appealing description of Fermion Mass Hierarchy (Agashe, Okui & Sundrum '08, PRA '12, v. Gersdorff, Quiros, Weichers '12)
- In Randall and Sundrum model, no 'bottom up' reason for Higgs to have special status as only brane localised field.
- Reduces electroweak (EW) and flavour constraints relative to brane localised Higgs.
- ...

EW constraints Vs. flavour constraints Vs. Higgs constraints

- BSM scenarios typically very constrained by EW precision tests (dominated by operators such as $|HDH|^2$ and $H^\dagger \sigma H A_{\mu\nu} B^{\mu\nu}$) and flavour constraints (dominated by $\bar{\psi}\psi\bar{\psi}\psi$).
- Higgs physics offers new constraints that bridges these largely independent constrains.

The Model

In coming paper all expressions derived for a generic 5D geometry, but here focus on slice of AdS_5;

$$ds^2 = \frac{R^2}{r^2}\left(\eta^{\mu\nu}dx_\mu dx_\nu - dr^2\right)$$

with $R \leqslant r \leqslant R'$, $1/R' \equiv M_{\rm KK} \sim \mathcal{O}(\rm TeV)$ and $R'/R \equiv \Omega \sim 10^{15}$. Higgs described by

$$S = \int d^5x\sqrt{G}\left[|D_M\Phi|^2 - V(\Phi)\right] + \int d^4x\sqrt{g_{\rm IR}}\left[-V_{\rm IR}(\Phi)\right] + \int d^4x\sqrt{g_{\rm UV}}\left[-V_{\rm UV}(\Phi)\right]$$

with

$$V(\Phi) = M_\Phi^2|\Phi|^2 \qquad V_{\rm IR}(\Phi) = -M_{\rm IR}|\Phi|^2 + \lambda_{\rm IR}|\Phi|^4 \qquad V_{\rm UV}(\Phi) = M_{\rm UV}|\Phi|^2$$

Higgs VEV

Higgs VEV is not constant but r dependant $\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h(r)\end{pmatrix}$, with

$$h(r) = N_h\left(r^{2+\beta} + B_h r^{2-\beta}\right)$$

where

$$\boxed{\beta = \sqrt{4 + R^2M_\Phi^2}} \qquad \text{and} \qquad B_h = -\frac{2+\beta - RM_{\rm UV}}{2-\beta-RM_{\rm UV}}R^{2\beta}$$

Scaling dimension of Higgs operator is then $2+\beta$. Without fine tuning, Higgs VEV always peaked towards IR brane, still resolves Gauge Hierarchy problem. (Cacciapalia, Csaki, Marandella & Terning '06)

$H \to WW$ (and $H \to ZZ$)

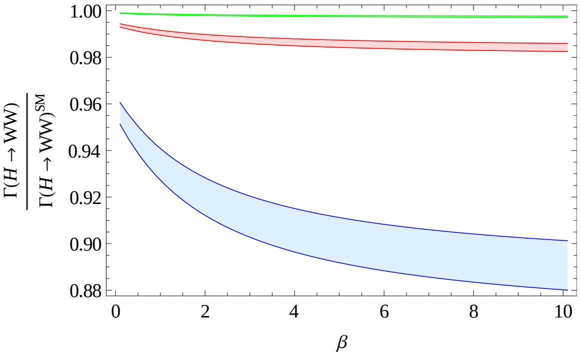


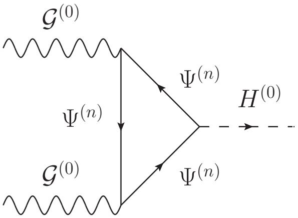
Figure: $H \to WW$ for $M_{\mathrm{KK}} = 1.5$ TeV (blue), 4 TeV (red) and 10 TeV (green).

- When $m_H \ll M_{KK}$, one can show for 5D generic geometries that, at tree level,

$$\frac{\Gamma(H \to WW)}{\Gamma(H \to WW)^{\mathrm{SM}}} \leqslant 1.$$

- However results sensitive to how one fits to EW precision observables or equivalently where in the $S - T$ ellipse you are sitting.
- In other words $H \to WW/ZZ$ should be included in EW χ^2 fits.

Gluon-Gluon Fusion



$$\sigma(\mathcal{G}\mathcal{G} \to H) \sim \sum_{U,D} \mathrm{Tr}\left(\mathbf{Y}_{U,D}\mathbf{M}^{-1}_{U,D}\right)$$

where

$$\mathbf{Y_U} = \frac{1}{\sqrt{2}}\begin{pmatrix} \tilde{Y}^{(0,0)}_{Q^i_L U^j_R} & 0 & \tilde{Y}^{(0,1)}_{Q^i_L U^j_R} & \cdots \\ \tilde{Y}^{(1,0)}_{Q^i_L U^j_R} & 0 & \tilde{Y}^{(1,1)}_{Q^i_L U^j_R} & \\ 0 & \tilde{Y}^{(1,1)*}_{Q^j_R U^i_L} & 0 & \\ \vdots & & & \ddots \end{pmatrix}$$

and

$$\mathbf{M_U} = \frac{1}{\sqrt{2}}\begin{pmatrix} Y^{(0,0)}_{Q^i_L U^j_R} & 0 & Y^{(0,1)}_{Q^i_L U^j_R} & \cdots \\ Y^{(1,0)}_{Q^i_L U^j_R} & m_1^{(Q^i)}\delta_{ij} & Y^{(1,1)}_{Q^i_L U^j_R} & \\ 0 & Y^{(1,1)*}_{Q^j_L U^i_R} & m_1^{(U^i)}\delta_{ij} & \\ \vdots & & & \ddots \end{pmatrix}.$$

- LO contribution now a loop process, receives contributions from full tower of KK fermions.
- Although KK fermions heavy, sizeable effect still found due to high multiplicity of modes, (different from pseudo-Goldstone Higgs scenarios).
- Full KK tower summed using completeness relations (Hirn & Sanz '07, Azatov, Toharia & Zhu '09)

Gluon-Gluon Fusion (Continued)

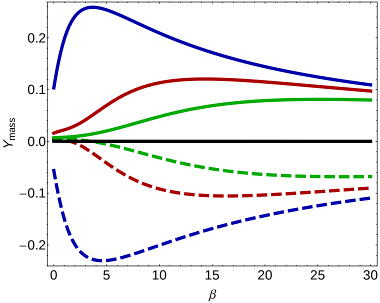


Figure: Yukawa couplings of the 1st, 2nd and 3rd KK modes in the mass eigenstate basis. Here consider simplified 1 generation model with $c_Q = 0.61$ and $c_U = -0.56$ and 5D Yukawa $Y_U = \sqrt{R}$. The lighter of the mass eigenstates are the dashed lines.

- With the exception of the zero mode, fermions in 5D are vector-like, i.e two mass eigenstates.
- When the Higgs is on the brane ($\beta \to \infty$), gluon-gluon fusion can be enhanced or suppressed, relative to SM result, depending on which limits you take first. (Azatov, Frank, Pourtolami, Toharia & Zhu '09 '13, Carena, Casagrande, Goertz, Haisch, Neubert, Pfof '10, '12 Malm, Neubert, Novotny & Schmell '13)
- With the Higgs in the bulk (for the model considered), the result is unambiguous, one finds an enhancement.

For Fermions with a bulk mass parameter $c_\chi R$ and a 5D Yukawa Y_χ, the effective zero mode Yukawa is

$$Y^{(0,0)}_{\psi^i_L \chi^j_R} \approx \frac{Y_\chi \tilde{v}}{\sqrt{R}} \sqrt{\frac{(1+\beta)(1-2c^i_\psi)(1+2c^j_\chi)}{(\Omega^{1-2c^i_\psi}-1)(\Omega^{1+2c^j_\chi}-1)}} \frac{\Omega^{1-c^i_\psi+c^j_\chi}-\Omega^{-1-\beta}}{2+\beta-c^i_\psi+c^j_\chi} \propto \frac{Y_\chi}{\sqrt{1+\beta}}$$

- Hence for large values of β, a larger 5D Yukawa is required in order to maintain correct quark masses.
- The size of the enhancement in Gluon-Gluon fusion is linearly sensitive to the 5D Yukawa, $Y_\chi\sqrt{1+\beta}$.
- Allowed size of 5D Yukawa couplings very important to stringent constraints from flavour physics, in particular ϵ_K.
- For a brane Higgs, NDA was used to estimate that $|Y_\chi|/\sqrt{R} \lesssim 3$, forcing $M_{\rm KK} \gtrsim 10-15$ TeV. (Csaki, Falkowski & Weiler '08).
- If one allows $|Y_\chi|/\sqrt{R} \lesssim 12$, stringent flavour constraints greatly reduced. (Bauer, Casagrande, Haisch & Neubert '09)

The allowed size of the 5D Yukawa couplings, of relevance to flavour constraints, now constrained not by perturbativity of the theory, but by Higgs physics.

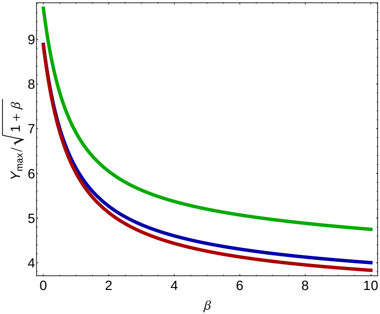


Figure: A NDA estimate of the size of the 5D Yukawa coupling at which one looses perturbative control of the theory, in units of $\sqrt{R}$. Asymptotes to 3 as $\beta \to \infty$.

Gluon-Gluon Fusion Results

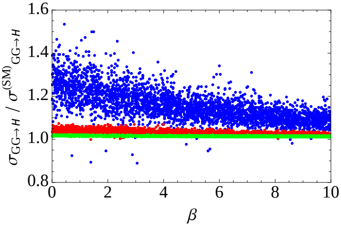


Figure: $|Y_\chi|/\sqrt{R} \leqslant 3$

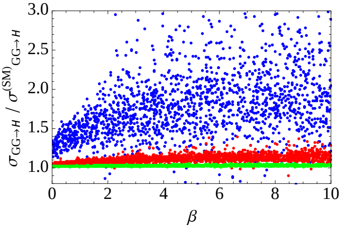


Figure: $|Y_\chi|/\sqrt{R} \leqslant 3\sqrt{1+\beta}$

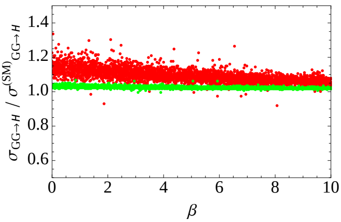


Figure: $|Y_\chi|/\sqrt{R} \leqslant 6$

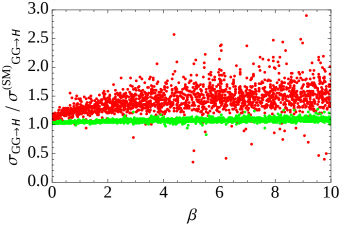


Figure: $|Y_\chi|/\sqrt{R} \leqslant 6\sqrt{1+\beta}$

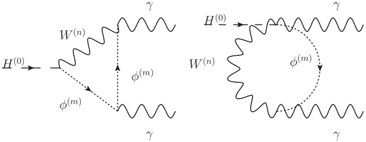
Gluon-Gluon fusion for $M_{\mathrm{KK}} = 1.5$ TeV (blue), 4 TeV (red) & 10 TeV (green). All points give correct quark masses and mixing angles.

$H \to \gamma\gamma$

- Again LO contribution is a loop process, receives contributions from charged scalars, vectors and fermions in model.
- Bulk Higgs models have extended scalar sector, arising from the mixing between 5th components of W and charged Higgs.
- Additional charged scalars quite heavy

$$m_n^{(\phi^\pm)} \sim \left(\frac{4n+1+2\beta}{4}\right)\frac{\pi}{R'}$$

- Logarithmically divergent diagrams such as



do not occur, due to gauge invariance forbidding the $\gamma - W - \phi$ vertex.
$Z - W - \phi$ vertex is allowed.

In practice, deviation from SM result is dominated by same fermion loop that contributes to gluon gluon fusion.

I.e an enhancement in gluon-gluon fusions gives a corresponding suppression in $H \to \gamma\gamma$.

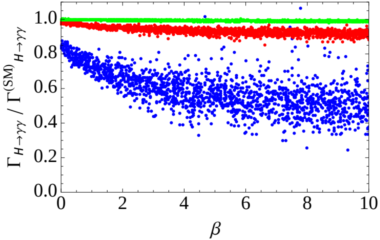


Figure: $M_{\mathrm{KK}} = 1.5,\ 4,\ 10$ TeV, $|Y_\chi|/\sqrt{R}\sqrt{1+\beta} \leqslant 3$

Comparison with Experiment

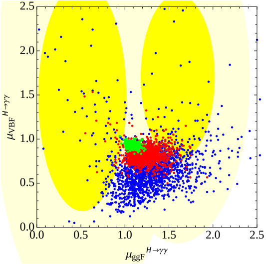


Figure: $M_{\mathrm{KK}} = 4$ TeV, $|Y_\chi|/\sqrt{R}\sqrt{1+\beta} \leqslant 3,\ 6,\ 10$

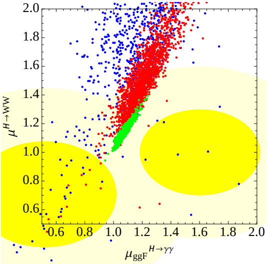


Figure: $M_{\mathrm{KK}} = 4$ TeV, $|Y_\chi|/\sqrt{R}\sqrt{1+\beta} \leqslant 3,\ 6,\ 10$

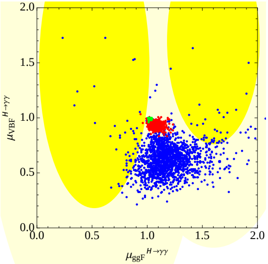


Figure: $M_{\mathrm{KK}} = 1.5,\ 4,\ 10$ TeV, $|Y_\chi|/\sqrt{R}\sqrt{1+\beta} \leqslant 3$

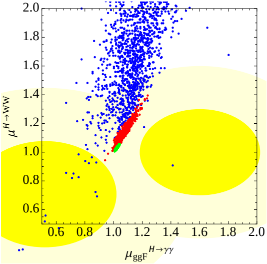


Figure: $M_{\mathrm{KK}} = 1.5,\ 4,\ 10$ TeV, $|Y_\chi|/\sqrt{R}\sqrt{1+\beta} \leqslant 3$

Conclusions

- Many possible BSM scenarios, for EW symmetry breaking, the question is how to distinguish between them.
- Even with low precision, Higgs physics offers constraints on BSM scenarios that compliment those coming from flavour and EW physics.
- A bulk Higgs offers a convenient toy model for investigating the effect of changing the scaling dimension of the Higgs, or equivalently a model of a partially composite Higgs.
- There are testable differences between different composite Higgs scenarios, e.g. sizeable modifications to $GG \to H$ in RS scenarios but typically not in pseudo-Goldstone Higgs models.

What about the future?

- Measurement of Higgs self coupling important in distinguishing between scenarios where the Higgs potential is generated at 1 loop (e.g. pseudo-Goldstone Higgs) and scenarios with fundamental potentials (e.g. this scenario).
- $H \to Z\gamma$ is both difficult to measure and also difficult to calculate but, unlike $H \to \gamma\gamma$, charged scalar contribution not 'protected' by gauge invariance.