Higgs phenomenology in the warped extra dimensions

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PRD80:035016,2009, AA, M.Toharia, L.Zhu
AA, M.Toharia, L.Zhu arXiv:1006.XXXX[hep-ph]

Outline

1 RS solution to the hierarchy problem

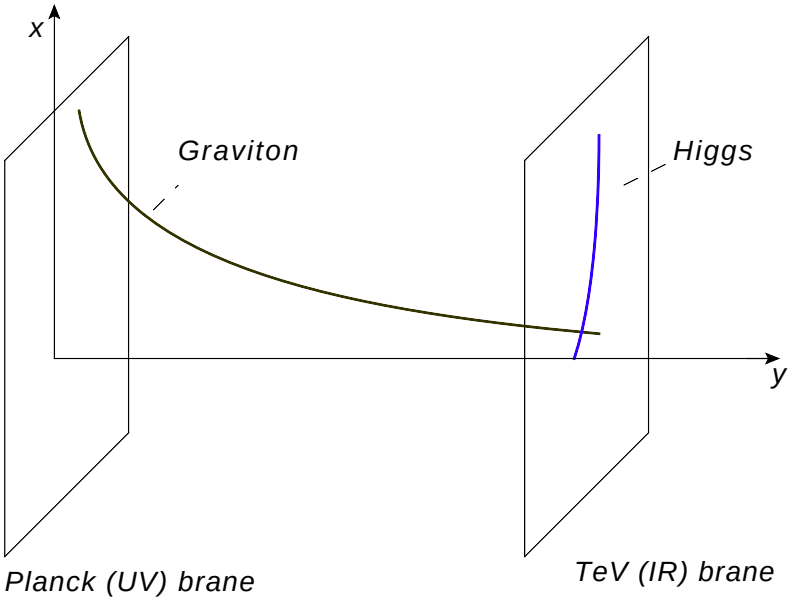
2 Standard Model in the bulk and RS GIM

3 Higgs phenomenology

4 Conclusion

Randall-Sundrum model

(Randall,Sundrum 99)

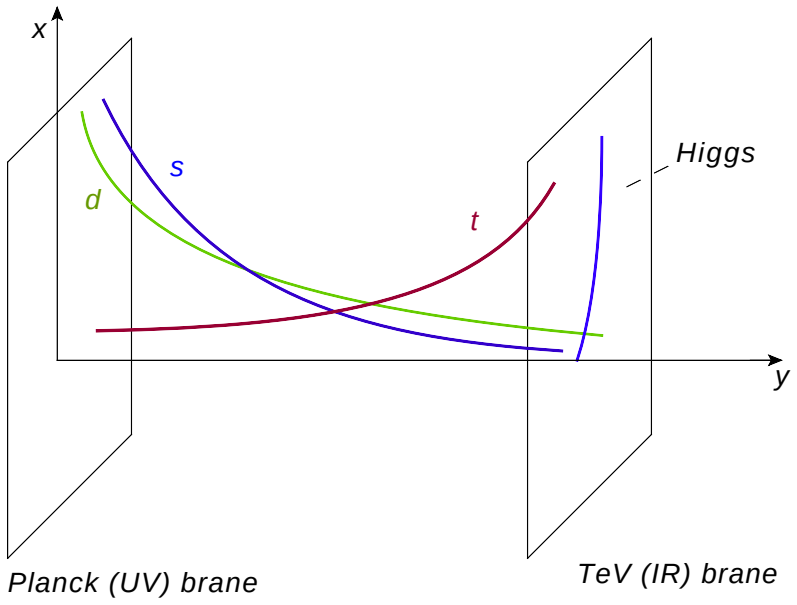


$$(ds)^2 = e^{-2ky} dx^2 - dy^2$$

- $$\frac{\Lambda_{TeV}}{M_{Pl}} \sim e^{-kL}$$

Fermions in the bulk

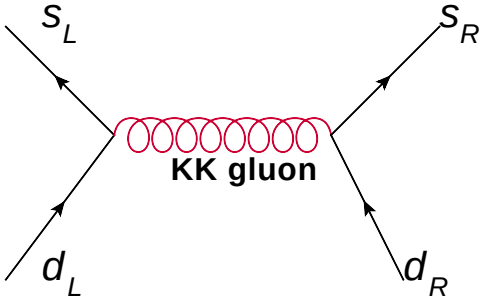
- One can easily explain large hierarchies in the fermion masses. *(Gherghetta, Pomarol; Grossman,Neubert...)*
- The mass is controlled by the fermion profile, $f(y) \propto e^{(1/2-c)ky}$
- Small variation in the 5D mass parameter c will lead to the large hierarchies in the fermion masses.
- Large flavor violating operators will be suppressed *(Agashe,Perez,Soni...)*



Flavor Anarchy

- Coupling to Higgs and and KK excitations are controlled by the values of the profiles at IR brane
  $\psi(c_i, y = \pi R) = f(c_i) \equiv \sqrt{\frac{1-2c_i}{1-(R/R')^{1-2c_i}}}, \quad \frac{R'}{R} = e^{kL}$
- 5D masses are similar $c_1 \sim c_2 \sim c_3$ but the values of the profiles are hierarchical $f(c_1) << f(c_2) << f(c_3)$
- Masses of the SM fermions: $m_{ij} = \frac{yv}{\sqrt{2}} f(c_i) f(c_j)$ are hierarchical
- Mixing matrices are hierarchical $V_{CKM} \sim (O_L^u)_{ij} \sim (O_L^d)_{ij} \sim \frac{f(c_i^q)}{f(c_j^q)}$
  $(O_R^u)_{ij} \sim \frac{f(c_i^u)}{f(c_j^u)}, (O_R^d)_{ij} \sim \frac{f(c_i^d)}{f(c_j^d)}, \quad i < j$

Bounds from low energy observables



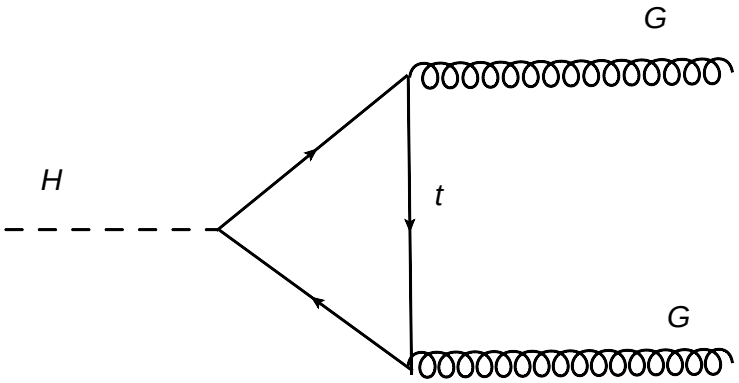
- $K_0 - \bar{K}_0$ oscillations, $\epsilon_K \sim g_{5D}^2 \frac{f(c_L^d)f(c_R^d)f(c_L^s)f(c_R^s)}{M_{KK}^2} \sim \frac{g_{5D}^2 m_d m_s}{Y_*^2 M_{KK}^2 v^2}$
- $M_{kk} \gtrsim 10(5)$ TeV - Brane(Bulk Higgs) Higgs

  (Csaki,Falkowski,Weiler;Blanke,Buras,Duling,Gori,Weiler;Casagrande,Goertz,Haisch,Neubert,Pfoh; AA,Agashe,Zhu;Perez,Gedalia)

- In the next part of my talk I will analyze couplings of the Higss to HGG and $H\gamma\gamma$
- three days ago on arXiv appeared paper (arXiv:1005.4315 [hep-ph] (Sandro Casagrande, Florian Goertz, Uli Haisch, Matthias Neubert, Torsten Pfoh)) where authors also analyzed these couplings.

Higgs coupling to the gluons

- In the SM Higgs to glue glue coupling arises dominantly from the diagram

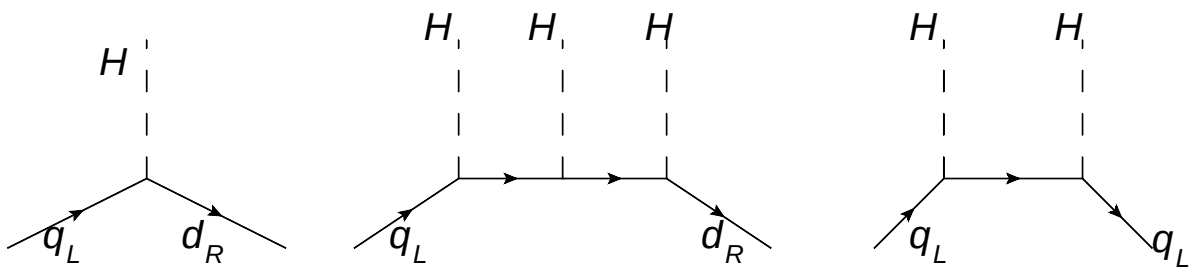


- In RS this contribution will be modified by the factor

$$\sim \frac{v}{M_{KK}^2} H G^{\mu\nu} G_{\mu\nu}$$

  - top Yukawa coupling is modified
  - vev of the Higgs is modified
  - KK modes of all the fermions running inside loop.

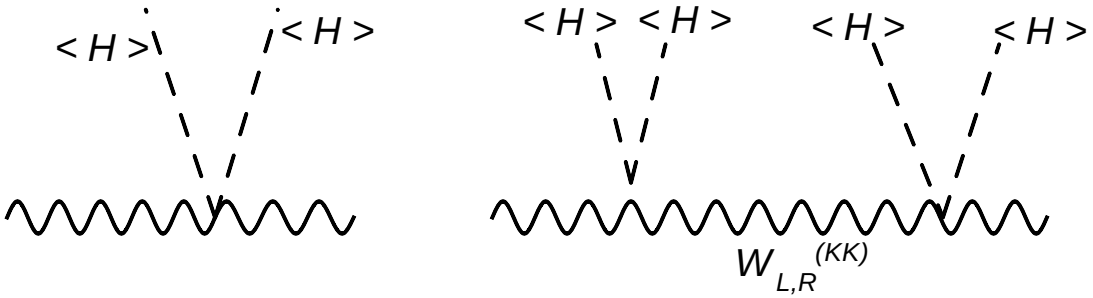
Modification of top Yukawa coupling



- $y_{ij} H \overline{Q}_{L_i} D_{R_j}, \quad \lambda_{ij} \frac{H^2}{\Lambda^2} \; H \overline{Q}_{L_i} D_{R_j}, \qquad k_{ij}^{Q} \frac{H^2}{\Lambda^2} \; \overline{Q}_{L_i} \partial\!\!\!/ Q_{L_j}$
- $m_{ij} = v \left(y_{ij} + \lambda_{ij} \frac{v^2}{\Lambda^2} \right) \overline{Q}_{L_i} D_{R_j}, \; Y_{ij} = \left(y_{ij} + 3\lambda_{ij} \frac{v^2}{\Lambda^2} \right) \frac{h}{\sqrt{2}} \overline{Q}_{L_i} D_{R_j}$
- $a_{tt} = 1 - \frac{Y_t v}{m_t \sqrt{2}} \sim Y_*^2 v^2 R'^2$
- same effect will lead to the flavor violation in the Higgs sector.

(Agashe,Contino;AA,Toharia,Zhu;Duling;Casagrande,Goertz,Haisch,Neubert,Pfoh.)

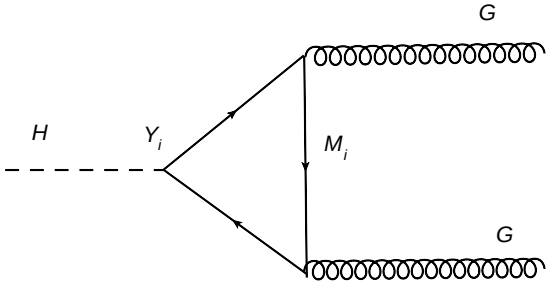
Higgs vev shift



- $M_w \neq \frac{1}{2} g < H >, \qquad < H > \equiv \tilde{v}$
- $v^2 = \tilde{v}^2 (1 - \frac{R'^2 \tilde{v}^2}{8R} \left(\tilde{g}_{5D}^2 + g_{5D}^2 \right))$, *($v = 246\,GeV$, SM Higgs vev)*
- $\frac{\tilde{v}}{v} \approx 1.05$ *($R'^{-1} = 1500\,TeV$, $g_{5D} = \tilde{g}_{5D}$)*
- If $\tilde{g}_{5D} > g_{5D}$ then it can lead to strong modification of the Higgs vev *(Bouchart, Moreau)*

Contribution of the heavy modes

- we want to study effects of the particles which are much heavier then the Higgs field so we can use use low energy theorems



- $\frac{\alpha}{12\pi}\frac{h}{v}G^{\mu\nu}G_{\mu\nu}\sum_{\text{Heavy}}\frac{Y_i}{M_i}$
- $\sum_{\text{All}}\frac{Y_i}{M_i}=\frac{\partial ln\left(DetM\right)}{\partial v}$

Calculating Determinant

- For simplicity we will start with one generation q -SM doublet, d SM singlet

$$M = \begin{pmatrix} Y_{qd}v & 0 & Y_{qD^1}v & 0 & Y_{qD^2} & \dots \\ Y_{Q^1d}v & M_{Q^1} & Y_{QD}v & 0 & Y_{QD_2} & \dots \\ 0 & Y_{D^1Q^1}v & M_{D^1} & Y_{D_1Q_2} & 0 & \dots \\ & & & M_{Q^2} & & \vdots \\ & & & & M_{D^2} & \\ \dots & \dots & \dots & \dots & \dots & \dots \end{pmatrix}$$

$$Y_{qd} \equiv \int dz \left(\frac{R}{z}\right)^5 q(z)d(z)H(z)$$

- $$DetM = y_{qd}v \prod_{l,n} M_{Q^l} M_{D^n} \left(1 - \sum_{i,j} \left[\frac{v^2 Y_{D^jQ^i} Y_{D^jQ^i}}{M_{Q^i} M_{D^j}} - \frac{v^2 Y_{Q^id} Y_{qD^j}}{Y_{qd} M_{Q^i} M_{D^j}}\right]\right) + O(v^5)$$

- In RS we have to sum infinite tower of KK modes

$$\frac{\partial \ln DetM}{\partial v} = \frac{1}{v}\left(1 + \sum_{i,j} \frac{2v^2 Y_{D_i Q_j}}{M_{Q^j} M_{D^i}} \left(-Y_{Q^j D^i} + \frac{Y_{Q^j d} Y_{qD^i}}{Y_{qd}}\right)\right) + O(v^3)$$

i, j refer to the KK modes.

- subtracting contribution of the zero modes

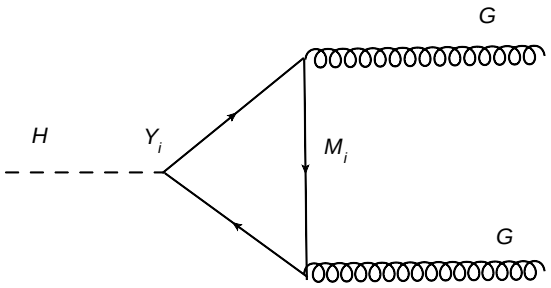
$$\sum_{\text{heavy}} \frac{Y}{M} = -\sum_{i,j} \frac{2v Y_{D_i Q_j} Y_{Q_j D_i}}{M_{Q^j} M_{D^i}} + O(v^3)$$

Performing KK sum

- $$\frac{Y_{D^i Q^j} Y_{Q^j D^i}}{M_{Q^j} M_{D^j}} = \int dz_1 dz_2 \left(\frac{R}{z_1}\right)^5 \left(\frac{R}{z_2}\right)^5 \cdot \frac{Q_R^{(j)}(z_1) Q_L^{(j)}(z_2)}{M_{Q^j}} \frac{D_L^{(i)}(z_1) D_R^{(i)}(z_2)}{M_{D^i}} H(z_1) H(z_2)$$
- using completeness relations one can prove that

$$\sum \frac{1}{M_{Q^n}} Q_R^{(n)}(z_1) Q_L^{(n)}(z_2) = -z_1^{2+c} z_2^{2-c} \theta(z_1 - z_2) + z_1^{2+c} z_2^{2-c} \frac{\left(\frac{z_1}{R}\right)^{1-2c} - 1}{\left(\frac{R'}{R}\right)^{1-2c} - 1}$$

Contribution of the KK fermions to the triangle diagram



$$\sum_{\text{Heavy}} \frac{Y^i}{M^i} = vR'^2 Y_*^2$$

- even KK towers of the light fermions will contribute significantly
- This result is NOT TRUE in the models where Higgs is PNGB.
  (Falkowski;Low,Rattazzi,Vichi)

Realistic Model

- Fermions should be in the multiplets of custodial $SU(2)_L \times SU(2)_R$ *(Agashe,Delgado,May,Sundrum)*
- $$SU(2)_L \text{ doublet } q = \begin{pmatrix} q_L^u(+,+) \\ q_L^d(+,+) \end{pmatrix},$$
$$SU(2)_R \text{ doublets } q_1 = \begin{pmatrix} q_L^{1,u}(+,-) \\ q_L^{1,d}(-,-) \end{pmatrix}, \quad q_2 = \begin{pmatrix} q_L^{2,u}(-,-) \\ q_L^{2,d}(+,-) \end{pmatrix}$$
- $$\mathcal{L}_{Yuk} = Y_{5D}^u \bar{q} q_2 H + Y_{5D}^d \bar{q} q_1 H$$

Ratio of Higgs to glue glue couplings

- Now we can present results

$$\frac{\text{HiggsGG}^{RS}}{\text{HiggsGG}^{SM}} = 1 + \frac{v^2 R'^2}{3F(\tau^{SM})} Tr\left[Y_*^u (Y_*^u)^\dagger + Y_*^d (Y_*^d)^\dagger\right] - a_{tt}\left[\text{where } a_{tt} \equiv \left(1 - \frac{Y_t v}{m_t\sqrt{2}}\right) \sim \bar{Y}_*^2 v^2 R'^2\right] - \frac{R'^2 v^2}{16R}\left(\tilde{g}_{5D}^2 + g_{5D}^2\right)$$

Numerical scan

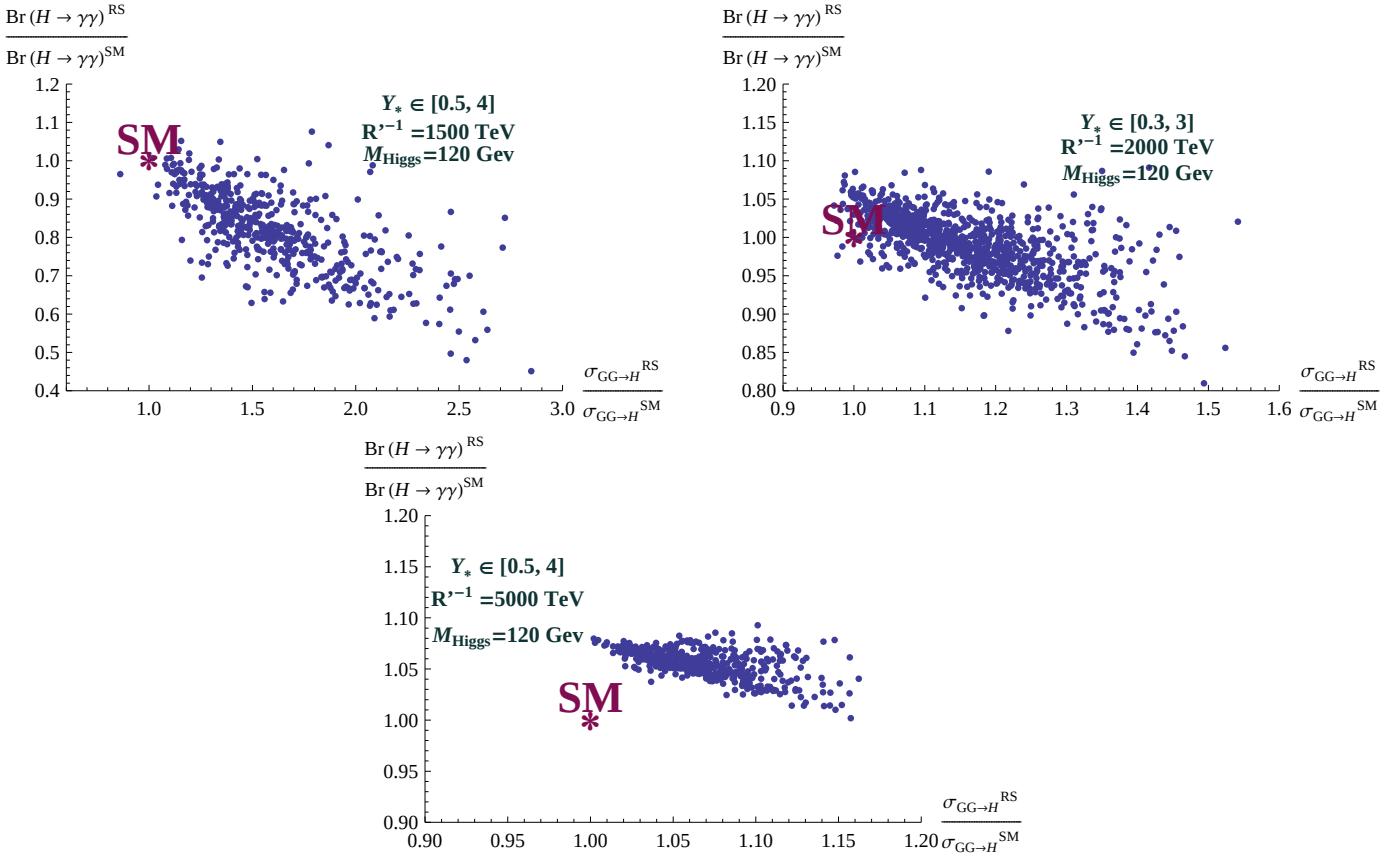


Figure: Modifications of the Higgs production from glue glue fusion and branching ratios to $\gamma\gamma$ ($R^{-1} \approx M_{kk}/2.5$)

Summary

- Warped extra dimensions with SM in the bulk provide a very attractive scenario of BSM physics
- Higgs couplings can be significantly modified.
- KK towers of light fermions provide a very important contribution to the HGG and $H\gamma\gamma$ couplings.
- Even for $M_{kk} \gtrsim 10\text{TeV}$ we can get up to 20% modification of the Higgs production from the glue glue fusion