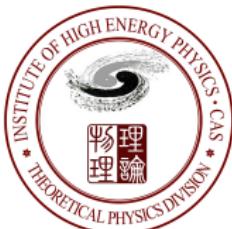


$\Delta S = 2$ decay in Warped Extra Dimensions

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Outline

- ▶ Introduction
- ▶ $b \rightarrow ss\bar{d}$ decay in the RS model with custodial protection
- ▶ $b \rightarrow ss\bar{d}$ decay in the bulk-Higgs RS model
- ▶ Summary

Introduction to RS model

- ▶ 5D spacetime with **warped** metric

[Randall, Sundrum, Phys. Rev. Lett. 83, 3370 (1999)]

$$ds^2 = e^{-2kr|\phi|} \eta_{\mu\nu} dx^\mu dx^\nu - r^2 d\phi^2, \quad \phi \in [-\pi, \pi].$$

- ▶ The fundamental scale is M_{Pl} , and the effective 4D electroweak scale is suppressed by a **magic exponential**

$$M_{EW} \sim e^{-kr\pi} M_{Pl} \sim \text{TeV}.$$

- ▶ natural explanation of **gauge hierarchy** problem.
- ▶ hierarchical structure of zero mode fermion profiles
 - Light fermions live close to **UV brane**.
 - Third generation localized closest to the **IR brane**.
- ▶ Kaluza-Klein (KK) excitations live close to the IR brane.
- ▶ Warped extra dimensions with **bulk fields** have explanation for **fermion masses** and **CKM hierarchies**.
- ▶ Tree level FCNCs ($b \rightarrow ss\bar{d}$).

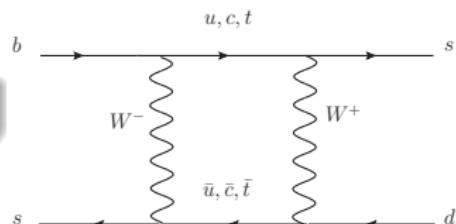
$b \rightarrow ss\bar{d}$ Channel

- Local $\Delta S = 2$ SM effective Hamiltonian for $b \rightarrow ss\bar{d}$ transition

$$\mathcal{H}_{\text{eff}}^{\Delta S=2} = \frac{G_F^2 m_W^2}{16\pi^2} \left(V_{td} V_{ts}^* V_{tb} V_{ts}^* S_0 \left(\frac{m_t^2}{m_W^2} \right) + V_{cd} V_{cs}^* V_{tb} V_{ts}^* S_0 \left(\frac{m_c^2}{m_W^2}, \frac{m_t^2}{m_W^2} \right) \right) \times [(\bar{s}d)_{V-A} (\bar{s}b)_{V-A}]$$

$$\mathcal{B}(B^+ \rightarrow K^+ K^+ \pi^-) < 1.1 \times 10^{-8}$$

[R. Aaij *et al.* (LHCb), Phys. Lett. B765, 307 (2017)]



- $b \rightarrow ss\bar{d}$ decay with very small strength in the SM serves as a sensitive probe for new physics.

$$\mathcal{B}(b \rightarrow ss\bar{d})_{\text{SM}} = (2.19 \pm 0.38) \times 10^{-12}$$

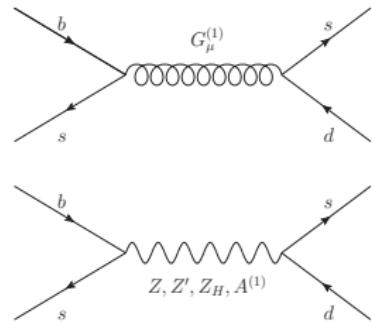
$b \rightarrow ss\bar{d}$ decay in the RS_c model

- The RS_c model is based on a single **warped extra dimension** with the bulk gauge group

$$\text{SU}(3)_c \times \text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_X \times P_{LR}$$

- $b \rightarrow ss\bar{d}$ decay receives **tree level contributions** from the **Kaluza-Klein (KK)** gluons, the heavy KK photons, new heavy electroweak (EW) gauge bosons Z_H and Z' , and in principle the Z^0 boson.
- Custodial protection of the $Z b_L \bar{b}_L$ coupling through the discrete P_{LR} symmetry renders tree-level Z^0 contributions negligible.
- The effective Hamiltonian for the $\Delta S = 2$ $b \rightarrow ss\bar{d}$ decay with the Wilson coefficients corresponding to $\mu = \mathcal{O}(M_{g^{(1)}})$

$$\begin{aligned} [\mathcal{H}_{\text{eff}}^{\Delta S=2}]_{KK} = & \frac{1}{2(M_{g^{(1)}})^2} [C_1^{VLL} \mathcal{Q}_1^{VLL} + C_1^{VRR} \mathcal{Q}_1^{VRR} \\ & + C_1^{LR} \mathcal{Q}_1^{LR} + C_2^{LR} \mathcal{Q}_2^{LR} + C_1^{RL} \mathcal{Q}_1^{RL} + C_2^{RL} \mathcal{Q}_2^{RL}]. \end{aligned}$$



$b \rightarrow ss\bar{d}$ decay in the RS_c model

$$\mathcal{Q}_1^{VLL} = (\bar{s}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_L d),$$

$$\mathcal{Q}_1^{VRR} = (\bar{s}\gamma_\mu P_R b)(\bar{s}\gamma^\mu P_R d),$$

$$\mathcal{Q}_1^{LR} = (\bar{s}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_R d),$$

$$\mathcal{Q}_2^{LR} = (\bar{s}P_L b)(\bar{s}P_R d),$$

$$\mathcal{Q}_1^{RL} = (\bar{s}\gamma_\mu P_R b)(\bar{s}\gamma^\mu P_L d),$$

$$\mathcal{Q}_2^{RL} = (\bar{s}P_R b)(\bar{s}P_L d),$$

$$[\Delta C_1^{VLL}(M_{g(1)})]^{\text{EW}} = 2[\Delta_L^{sb}(Z^{(1)})\Delta_L^{sd}(Z^{(1)}) + \Delta_L^{sb}(Z_X^{(1)})\Delta_L^{sd}(Z_X^{(1)})],$$

$$[\Delta C_1^{VRR}(M_{g(1)})]^{\text{EW}} = 2[\Delta_R^{sb}(Z^{(1)})\Delta_R^{sd}(Z^{(1)}) + \Delta_R^{sb}(Z_X^{(1)})\Delta_R^{sd}(Z_X^{(1)})],$$

$$[\Delta C_1^{LR}(M_{g(1)})]^{\text{EW}} = 2[\Delta_L^{sb}(Z^{(1)})\Delta_R^{sd}(Z^{(1)}) + \Delta_L^{sb}(Z_X^{(1)})\Delta_R^{sd}(Z_X^{(1)})],$$

$$[\Delta C_1^{RL}(M_{g(1)})]^{\text{EW}} = 2[\Delta_R^{sb}(Z^{(1)})\Delta_L^{sd}(Z^{(1)}) + \Delta_R^{sb}(Z_X^{(1)})\Delta_L^{sd}(Z_X^{(1)})],$$

$$[C_1^{VLL}(M_{g(1)})]^G = \frac{2}{3} p_{UV}^2 \Delta_L^{sb} \Delta_L^{sd},$$

$$[C_1^{VRR}(M_{g(1)})]^G = \frac{2}{3} p_{UV}^2 \Delta_R^{sb} \Delta_R^{sd},$$

$$[C_1^{LR}(M_{g(1)})]^G = -\frac{1}{3} p_{UV}^2 \Delta_L^{sb} \Delta_R^{sd},$$

$$[C_2^{LR}(M_{g(1)})]^G = -2 p_{UV}^2 \Delta_L^{sb} \Delta_R^{sd},$$

$$[C_1^{RL}(M_{g(1)})]^G = -\frac{1}{3} p_{UV}^2 \Delta_R^{sb} \Delta_L^{sd},$$

$$[C_2^{RL}(M_{g(1)})]^G = -2 p_{UV}^2 \Delta_R^{sb} \Delta_L^{sd},$$

$$[\Delta C_1^{VLL}(M_{g(1)})]^{\text{QED}} = 2[\Delta_L^{sb}(A^{(1)})][\Delta_L^{sd}(A^{(1)})],$$

$$[\Delta C_1^{VRR}(M_{g(1)})]^{\text{QED}} = 2[\Delta_R^{sb}(A^{(1)})][\Delta_R^{sd}(A^{(1)})],$$

$$[\Delta C_1^{LR}(M_{g(1)})]^{\text{QED}} = 2[\Delta_L^{sb}(A^{(1)})][\Delta_R^{sd}(A^{(1)})],$$

$$[\Delta C_1^{RL}(M_{g(1)})]^{\text{QED}} = 2[\Delta_R^{sb}(A^{(1)})][\Delta_L^{sd}(A^{(1)})].$$

$b \rightarrow ss\bar{d}$ decay in the RS_c model

$$\begin{aligned} C_1^{VLL}(M_{g^{(1)}}) &= [0.67 + 0.02 + 0.56] \tilde{\Delta}_L^{sb} \tilde{\Delta}_L^{sd} = 1.25 \tilde{\Delta}_L^{sb} \tilde{\Delta}_L^{sd}, \\ C_1^{VRR}(M_{g^{(1)}}) &= [0.67 + 0.02 + 0.98] \tilde{\Delta}_R^{sb} \tilde{\Delta}_R^{sd} = 1.67 \tilde{\Delta}_R^{sb} \tilde{\Delta}_R^{sd}, \\ C_1^{LR}(M_{g^{(1)}}) &= [-0.333 + 0.02 + 0.56] \tilde{\Delta}_L^{sb} \tilde{\Delta}_R^{sd} = 0.25 \tilde{\Delta}_L^{sb} \tilde{\Delta}_R^{sd}, \\ C_1^{RL}(M_{g^{(1)}}) &= [-0.333 + 0.02 + 0.56] \tilde{\Delta}_R^{sb} \tilde{\Delta}_L^{sd} = 0.25 \tilde{\Delta}_R^{sb} \tilde{\Delta}_L^{sd}, \end{aligned}$$

After RG running of the Wilson coefficients to a low energy scale $\mu_b = 4.6$ GeV, the decay width in the RS_c model

$$\begin{aligned} \Gamma &= \frac{m_b^5}{3072(2\pi)^3(M_{g^{(1)}})^4} [16(|C_1^{VLL}(\mu_b)|^2 + |C_1^{VRR}(\mu_b)|^2) \\ &\quad + 12(|C_1^{LR}(\mu_b)|^2 + |C_1^{RL}(\mu_b)|^2) + 3(|C_2^{LR}(\mu_b)|^2 + |C_2^{RL}(\mu_b)|^2) \\ &\quad - 2\mathcal{R}e(C_1^{LR}(\mu_b)C_2^{*LR}(\mu_b) + C_2^{LR}(\mu_b)C_1^{*LR}(\mu_b) \\ &\quad + C_1^{RL}(\mu_b)C_2^{*RL}(\mu_b) + C_2^{RL}(\mu_b)C_1^{*RL}(\mu_b))]. \end{aligned}$$

$b \rightarrow ss\bar{d}$ decay in the bulk-Higgs RS model

- ▶ The bulk-Higgs RS model is based on the 5D gauge group $SU(3)_c \times SU(2)_V \times U(1)_Y$, where all the fields propagate in the 5D spacetime.
- ▶ $b \rightarrow ss\bar{d}$ decay in the bulk-Higgs RS model results from **tree-level exchanges** of Kaluza-Klein gluons and photons, the Z^0 boson and the Higgs boson as well as their KK excitations and the extended scalar fields $\phi^{Z(n)}$.
- ▶ We consider the summation over the contributions from the entire KK towers, with the lightest KK states having mass $M_{g^{(1)}} \approx 2.45 M_{KK}$.

$$[\mathcal{H}_{\text{eff}}^{\Delta S=2}]_{KK} = \sum_{n=1}^5 [C_n \mathcal{O}_n + \tilde{C}_n \tilde{\mathcal{O}}_n],$$

$$\mathcal{O}_1 = (\bar{s}_L \gamma_\mu b_L)(\bar{s}_L \gamma^\mu d_L),$$

$$\mathcal{O}_2 = (\bar{s}_R b_L)(\bar{s}_R d_L),$$

$$\mathcal{O}_3 = (\bar{s}_R^\alpha b_L^\beta)(\bar{s}_R^\beta d_L^\alpha),$$

$$\mathcal{O}_4 = (\bar{s}_R b_L)(\bar{s}_L d_R),$$

$$\mathcal{O}_5 = (\bar{s}_R^\alpha b_L^\beta)(\bar{s}_L^\beta d_R^\alpha).$$

$b \rightarrow ss\bar{d}$ decay in the bulk-Higgs RS model

$$C_1 = \frac{4\pi L}{M_{KK}^2} (\tilde{\Delta}_D)_{23} \otimes (\tilde{\Delta}_D)_{21} \left[\frac{\alpha_s}{2} \left(1 - \frac{1}{N_c}\right) + \alpha Q_d^2 + \frac{\alpha}{s_w^2 c_w^2} (T_3^d - Q_d s_w^2)^2 \right],$$

$$\tilde{C}_1 = \frac{4\pi L}{M_{KK}^2} (\tilde{\Delta}_d)_{23} \otimes (\tilde{\Delta}_d)_{21} \left[\frac{\alpha_s}{2} \left(1 - \frac{1}{N_c}\right) + \alpha Q_d^2 + \frac{\alpha}{s_w^2 c_w^2} (-Q_d s_w^2)^2 \right],$$

$$C_4 = -\frac{4\pi L \alpha_s}{M_{KK}^2} (\tilde{\Delta}_D)_{23} \otimes (\tilde{\Delta}_d)_{21} - \frac{L}{\pi \beta M_{KK}^2} (\tilde{\Omega}_d)_{23} \otimes (\tilde{\Omega}_D)_{21},$$

$$\tilde{C}_4 = -\frac{4\pi L \alpha_s}{M_{KK}^2} (\tilde{\Delta}_d)_{23} \otimes (\tilde{\Delta}_D)_{21} - \frac{L}{\pi \beta M_{KK}^2} (\tilde{\Omega}_D)_{23} \otimes (\tilde{\Omega}_d)_{21},$$

$$C_5 = \frac{4\pi L}{M_{KK}^2} (\tilde{\Delta}_D)_{23} \otimes (\tilde{\Delta}_d)_{21} \left[\frac{\alpha_s}{N_c} - 2\alpha Q_d^2 + \frac{2\alpha}{s_w^2 c_w^2} (T_3^d - Q_d s_w^2)(Q_d s_w^2) \right],$$

$$\tilde{C}_5 = \frac{4\pi L}{M_{KK}^2} (\tilde{\Delta}_d)_{23} \otimes (\tilde{\Delta}_D)_{21} \left[\frac{\alpha_s}{N_c} - 2\alpha Q_d^2 + \frac{2\alpha}{s_w^2 c_w^2} (T_3^d - Q_d s_w^2)(Q_d s_w^2) \right],$$

$b \rightarrow ss\bar{d}$ decay in the bulk-Higgs RS model

$$(\tilde{\Delta}_D)_{23} \otimes (\tilde{\Delta}_d)_{21} \rightarrow (U_d^\dagger)_{2i} (U_d)_{i3} (\tilde{\Delta}_{Dd})_{ij} (W_d^\dagger)_{2j} (W_d)_{j1},$$

$$(\tilde{\Delta}_{Dd})_{ij} = \frac{F^2(c_{Q_i})}{3 + 2c_{Q_i}} \frac{3 + c_{Q_i} + c_{d_j}}{2(2 + c_{Q_i} + c_{d_j})} \frac{F^2(c_{d_j})}{3 + 2c_{d_j}},$$

$$(\tilde{\Omega}_D)_{23} \otimes (\tilde{\Omega}_d)_{21} \rightarrow (U_d^\dagger)_{2i} (W_d)_{j3} (\tilde{\Omega}_{Dd})_{ijkl} (W_d^\dagger)_{2k} (U_d)_{l1},$$

$$\begin{aligned} (\tilde{\Omega}_{Dd})_{ijkl} &= \frac{\pi(1+\beta)}{4L} \frac{F(c_{Q_i})F(c_{d_j})}{2+\beta+c_{Q_i}+c_{d_j}} \frac{(Y_d)_{ij}(Y_d^\dagger)_{kl}}{1} \\ &\times \frac{(4+2\beta+c_{Q_i}+c_{d_j}+c_{d_k}+c_{Q_l})}{4+c_{Q_i}+c_{d_j}+c_{d_k}+c_{Q_l}} \frac{F(c_{d_k})F(c_{Q_l})}{2+\beta+c_{d_k}+c_{Q_l}}, \end{aligned}$$

The decay width in the bulk-Higgs RS model

$$\begin{aligned} \Gamma &= \frac{m_b^5}{3072(2\pi)^3} [64(|C_1(\mu_b)|^2 + |\tilde{C}_1(\mu_b)|^2) \\ &+ 12(|C_4(\mu_b)|^2 + |\tilde{C}_4(\mu_b)|^2 + |C_5(\mu_b)|^2 + |\tilde{C}_5(\mu_b)|^2) \\ &+ 4\Re(C_4(\mu_b)C_5^*(\mu_b) + C_4^*(\mu_b)C_5(\mu_b) \\ &+ \tilde{C}_4(\mu_b)\tilde{C}_5^*(\mu_b) + \tilde{C}_4^*(\mu_b)\tilde{C}_5(\mu_b))]. \end{aligned}$$

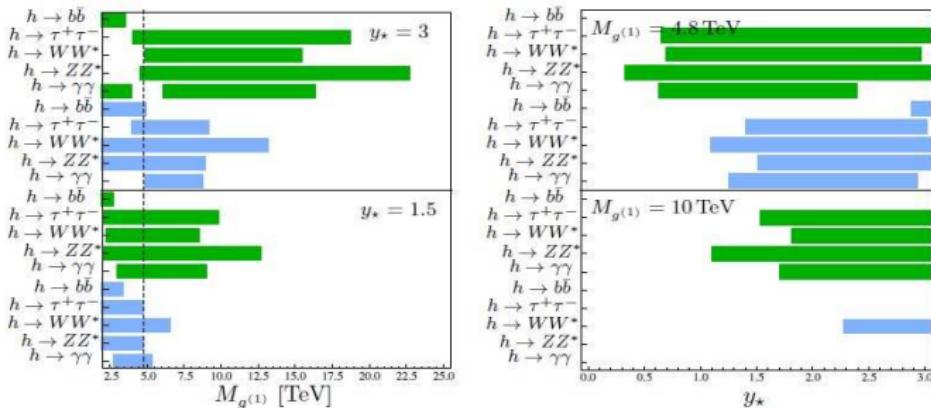
Phenomenological bounds on RS models

► The RS_c model

■ Constraint from tree-level analysis of the S and T parameters

[Malm, Neubert, Novotny, Schmell, JHEP 01 (2014) 173]

$$M_{g(1)} > 4.8 \text{ TeV} \quad (95\% \text{ CL}).$$



[Malm, Neubert, Schmell, JHEP 02 (2015) 008]

■ Stringent bounds emerge from the signal rates for $pp \rightarrow h \rightarrow ZZ^*, WW^*$, at 95% CL

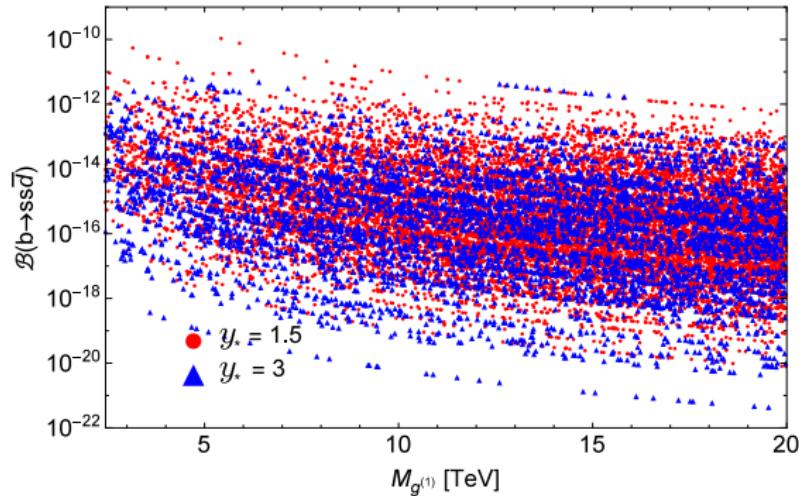
$$M_{g(1)}|_{\text{brane-Higgs}}^{\text{custodial RS}} > 22.7 \text{ TeV} \times \left(\frac{y^*}{3}\right), \quad M_{g(1)}|_{\text{narrow Higgs}}^{\text{bulk-}} > 13.2 \text{ TeV} \times \left(\frac{y^*}{3}\right)$$

Branching ratio of $b \rightarrow ss\bar{d}$ in the RS_c model

ΔM_K , ϵ_K and ΔM_{B_s} constraints

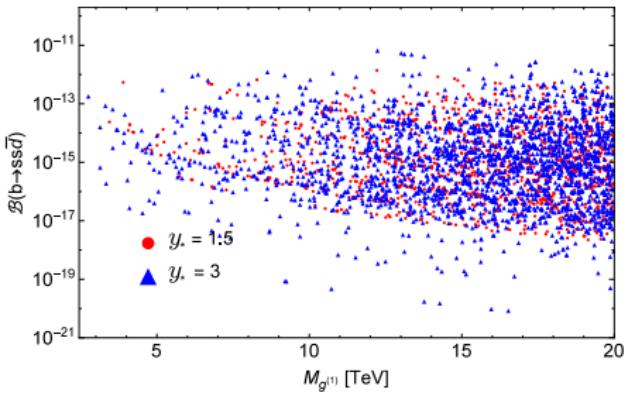
KK gluons dominant

Comparable Z_H and Z' contributions



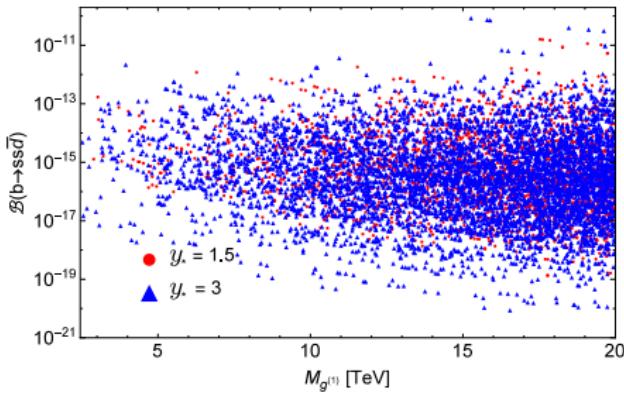
Branching ratio in the bulk-Higgs RS model

broad Higgs profile



$$\beta = 1$$

narrow Higgs profile



$$\beta = 10$$

Summary

- ▶ In both models, the main contribution to the $b \rightarrow ss\bar{d}$ decay comes from tree level exchanges of KK gluons, while in the RS_c model the contributions from the new heavy EW gauge bosons Z_H and Z' can compete with the KK-gluon contributions.
- ▶ We employed renormalization group runnings of the Wilson coefficients with NLO QCD factors in both models.
- ▶ The RS_c model enhances the branching ratio, compared to the SM result, by two order of magnitude for some points in the parameter space with $y_* = 1.5$.
- ▶ In the bulk-Higgs RS model with $\beta = 10$, it is possible to achieve an order of magnitude enhancement of the branching ratio for some of the parameter points.

THANK YOU!