$b \to ss\bar{d}$ decay in Randall-Sundrum models

Faisal Munir
IHEP, Beijing
Supervisor: Cai-Dian Lü

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Outline

- Introduction
- $b \to ss\bar{d}$ decay in the RS model with custodial protection
- $b \to ss\bar{d}$ 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)]

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

- 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 ($b \to ss\bar{d}$).

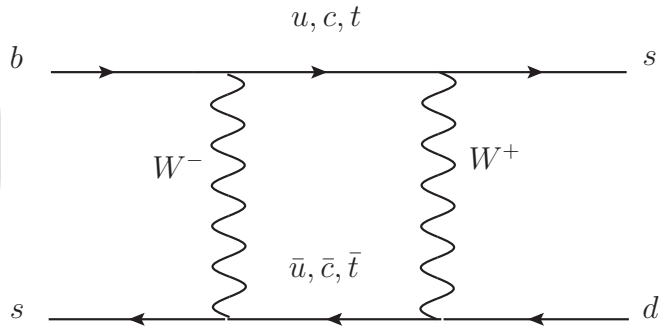
$b \to ss\bar{d}$ Channel

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

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

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

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



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

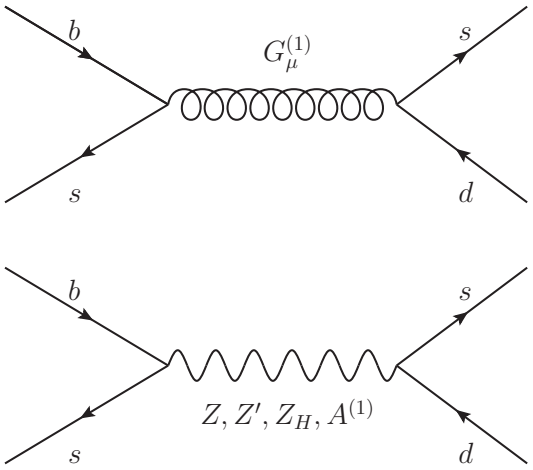
$$\mathcal{B}(b \to ss\bar{d})_{\text{SM}} = (2.19 \pm 0.38) \times 10^{-12}$$

$b \to ss\bar{d}$ decay in the RS$_c$ model

- The RS$_c$ model is based on a single warped extra dimension with the bulk gauge group

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

- $b \to ss\bar{d}$ 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 $Zb_L\bar{b}_L$ coupling through the discrete P_{LR} symmetry renders tree-level Z^0 contributions negligible.
- The effective Hamiltonian for the $\Delta S = 2$ $b \to ss\bar{d}$ decay with the Wilson coefficients corresponding to $\mu = \mathcal{O}(M_{g^{(1)}})$



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

$b \to ss\bar{d}$ decay in the RS$_c$ model

$$\mathcal{Q}_1^{VLL} = (\bar{s}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_L d),$$
$$\mathcal{Q}_1^{VRR} = (\bar{s}\gamma_\mu P_R b)(\bar{s}\gamma^\mu P_R d),$$
$$\mathcal{Q}_1^{LR} = (\bar{s}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_R d),$$
$$\mathcal{Q}_2^{LR} = (\bar{s}P_L b)(\bar{s}P_R d),$$
$$\mathcal{Q}_1^{RL} = (\bar{s}\gamma_\mu P_R b)(\bar{s}\gamma^\mu P_L d),$$
$$\mathcal{Q}_2^{RL} = (\bar{s}P_R b)(\bar{s}P_L d),$$

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

$$[C_1^{VLL}(M_{g^{(1)}})]^G = \tfrac{2}{3}{p_{\mathsf{UV}}}^2\Delta_L^{sb}\Delta_L^{sd},$$
$$[C_1^{VRR}(M_{g^{(1)}})]^G = \tfrac{2}{3}{p_{\mathsf{UV}}}^2\Delta_R^{sb}\Delta_R^{sd},$$
$$[C_1^{LR}(M_{g^{(1)}})]^G = -\tfrac{1}{3}{p_{\mathsf{UV}}}^2\Delta_L^{sb}\Delta_R^{sd},$$
$$[C_2^{LR}(M_{g^{(1)}})]^G = -2{p_{\mathsf{UV}}}^2\Delta_L^{sb}\Delta_R^{sd},$$
$$[C_1^{RL}(M_{g^{(1)}})]^G = -\tfrac{1}{3}{p_{\mathsf{UV}}}^2\Delta_R^{sb}\Delta_L^{sd},$$
$$[C_2^{RL}(M_{g^{(1)}})]^G = -2{p_{\mathsf{UV}}}^2\Delta_R^{sb}\Delta_L^{sd},$$

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

$b \to ss\bar{d}$ decay in the RS$_c$ model

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

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

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

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

- The bulk-Higgs RS model is based on the 5D gauge group $\mathsf{SU}(3)_c \times \mathsf{SU}(2)_V \times \mathsf{U}(1)_Y$, where all the fields propagate in the 5D spacetime.
- $b \to ss\bar{d}$ 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 $M_{g^{(1)}} \approx 2.45\ M_{\mathsf{KK}}$.

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

$$\mathcal{O}_1 = (\bar{s}_L \gamma_\mu b_L)(\bar{s}_L \gamma^\mu d_L),$$
$$\mathcal{O}_2 = (\bar{s}_R b_L)(\bar{s}_R d_L),$$
$$\mathcal{O}_3 = (\bar{s}_R^\alpha b_L^\beta)(\bar{s}_R^\beta d_L^\alpha),$$
$$\mathcal{O}_4 = (\bar{s}_R b_L)(\bar{s}_L d_R),$$
$$\mathcal{O}_5 = (\bar{s}_R^\alpha b_L^\beta)(\bar{s}_L^\beta d_R^\alpha).$$

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

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

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

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

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

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

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

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

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

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

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

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

The decay width in the bulk-Higgs RS model

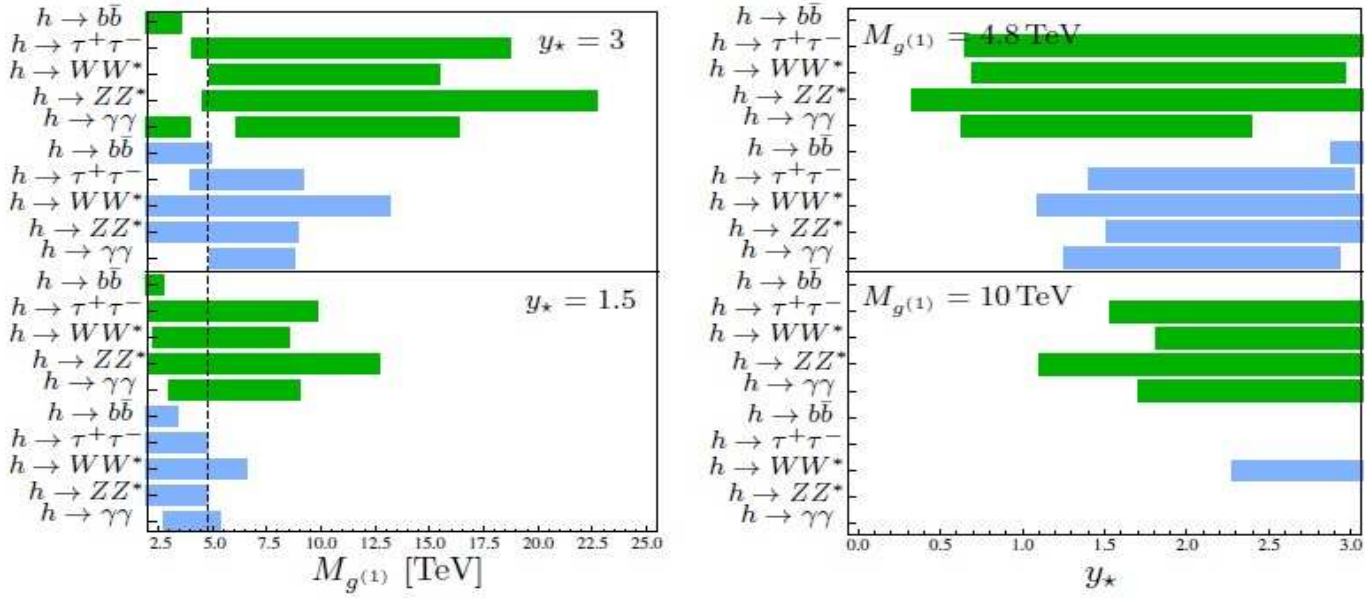
$$\begin{aligned}\Gamma = \frac{m_b^5}{3072(2\pi)^3}[&64(|C_1(\mu_b)|^2 + |\tilde{C}_1(\mu_b)|^2) \\ &+ 12(|C_4(\mu_b)|^2 + |\tilde{C}_4(\mu_b)|^2 + |C_5(\mu_b)|^2 + |\tilde{C}_5(\mu_b)|^2) \\ &+ 4\mathcal{R}e(C_4(\mu_b)C_5^*(\mu_b) + C_4^*(\mu_b)C_5(\mu_b) \\ &+ \tilde{C}_4(\mu_b)\tilde{C}_5^*(\mu_b)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

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]

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



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

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

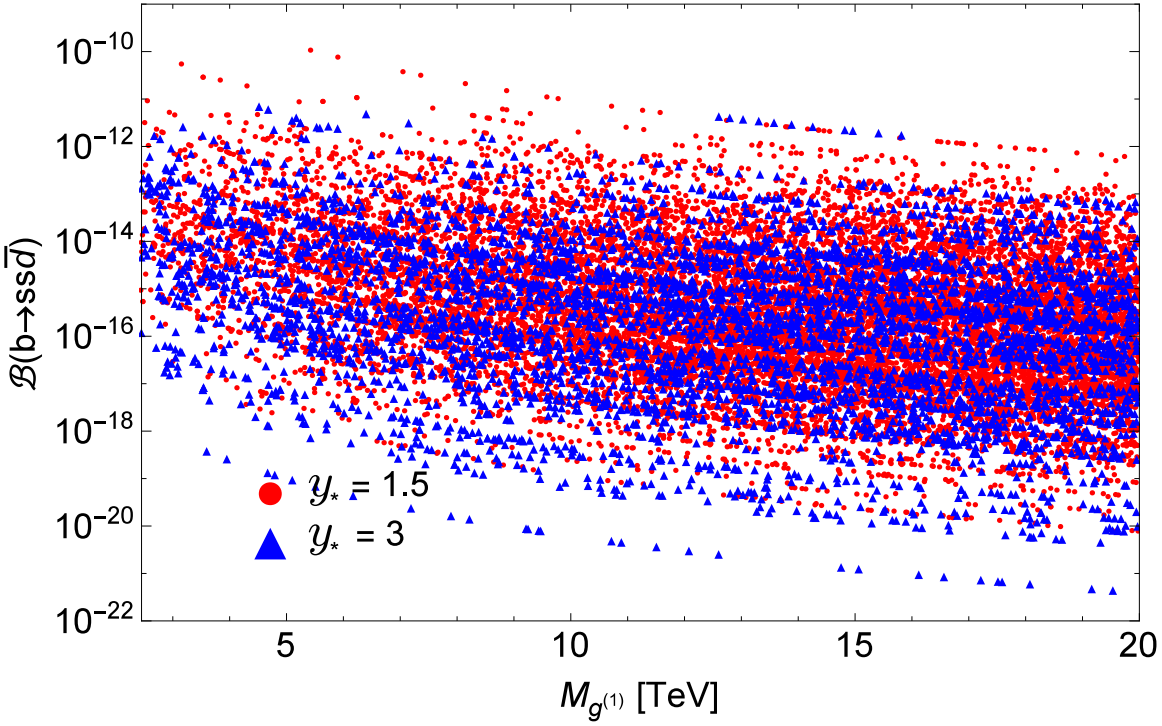
$$M_{g^{(1)}}\Big|^{\text{custodial RS}}_{\text{brane-Higgs}} > 22.7 \text{ TeV} \times \left(\frac{y_\star}{3}\right), \quad M_{g^{(1)}}\Big|^{\text{custodial RS}}_{\text{narrow bulk-Higgs}} > 13.2 \text{ TeV} \times \left(\frac{y_\star}{3}\right)$$

Branching ratio of $b \to ss\bar{d}$ in the RS$_c$ model

ΔM_K, ϵ_K and ΔM_{B_s} constraints

KK gluons dominant

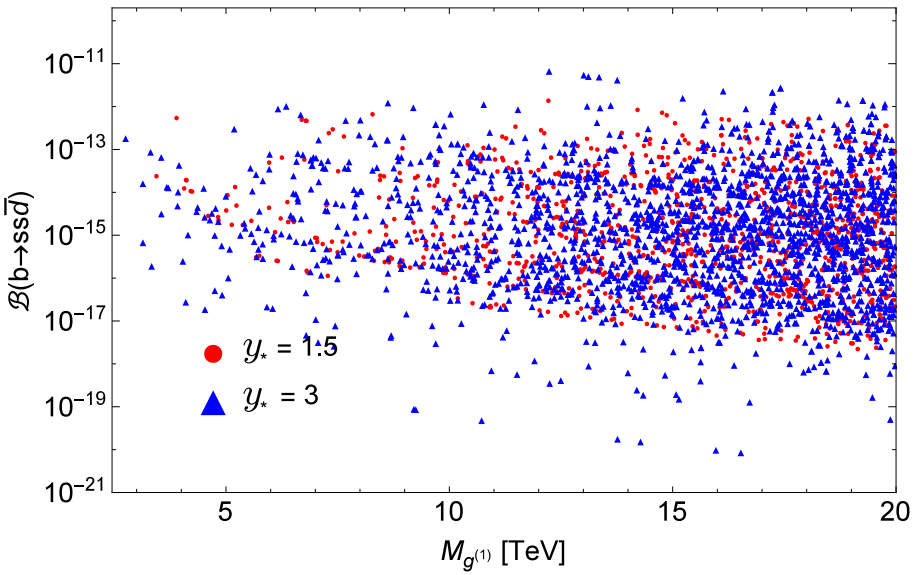
Comparable Z_H and Z' contributions



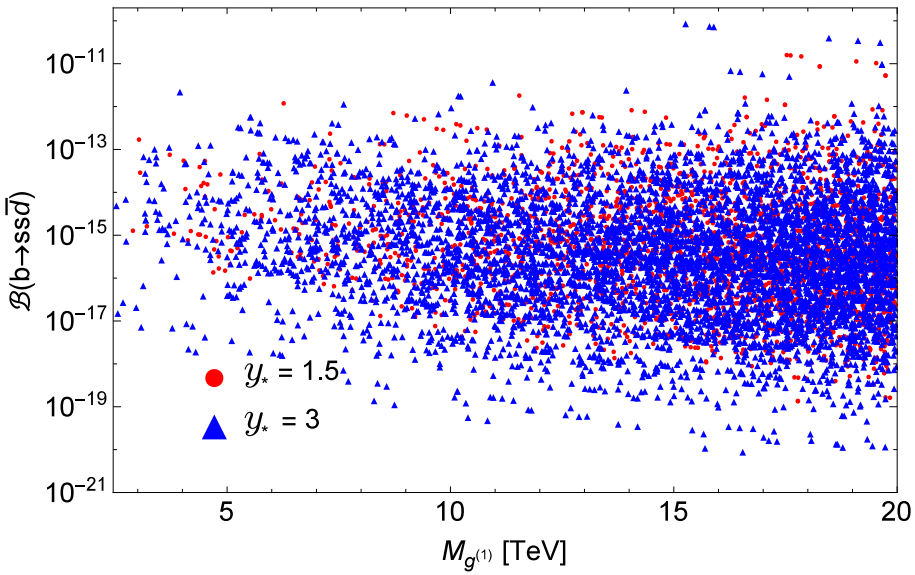
Branching ratio in the bulk-Higgs RS model

broad Higgs profile

narrow Higgs profile



$\beta = 1$



$\beta = 10$

Summary

- In both models, the main contribution to the $b \to ss\bar{d}$ 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 $y_\star = 1.5$.
- 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!