Flavor Physics in Extra Dimensions

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in cooperation with C.-D. Lu and M. Neubert

Outline

- **Introduction**
- **Theoretical Preparation**
- **Phenomenological Analysis**
  - S, T & U parameters
  - Zbb couplings
  - Right-handed charged weak current
  - Top rare decays
  - Neutral meson mixing
  - B meson rare decays
- **Conclusion and Outlook**

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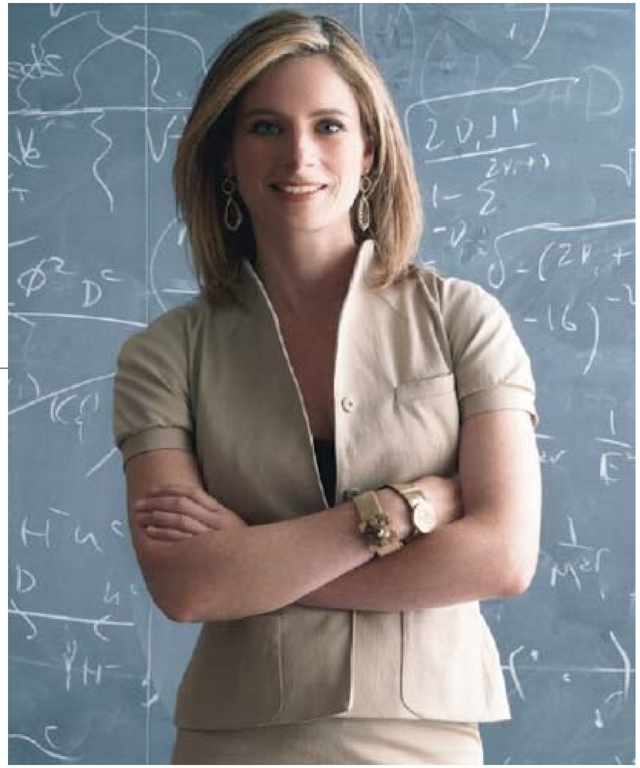
Introduction



- In 1999, to solve the **gauge hierarchy problem**, Lisa Randall and Raman Sundrum introduced one extra **warped dimension** to the 4D space-time [arXiv:hep-ph/9905221], with the metric given by,

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

The fundamental scale is M_{pl}, and the effective 4D electroweak scale is suppressed by a magic exponential,

$$M_{ew} \sim M_{pl}e^{-L} \sim \text{TeV}.$$

- **Fermion mass hierarchies** are generated by the magic exponentials,

$$m_q \propto e^{2c_q},\ m_l \propto e^{2c_l},\ m_\nu \propto e^{2c_\nu},$$

in the Randall-Sundrum model, and the right structure of the **CKM matrix** are also obtained.

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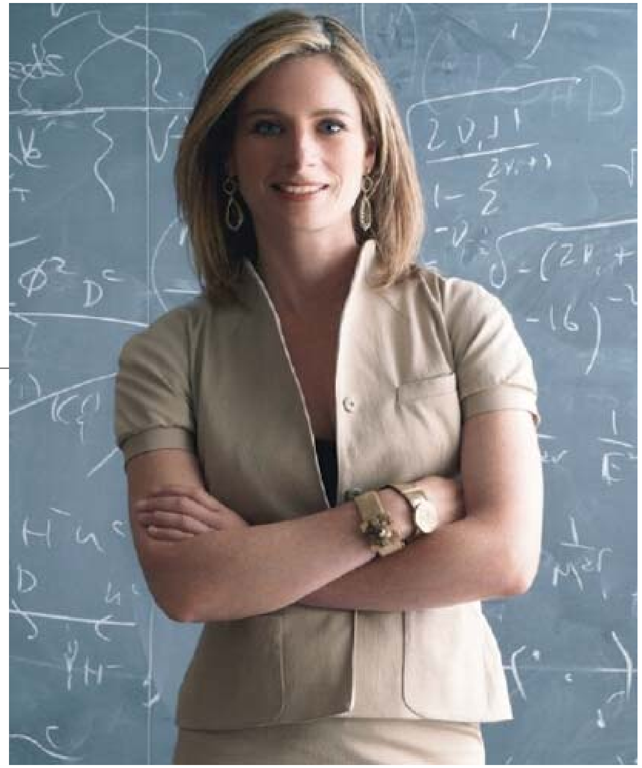

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$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}$$

The fundamental scale is M_p
scale is suppressed by a ma

$$M_{ew} \sim$$

$$V_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

k

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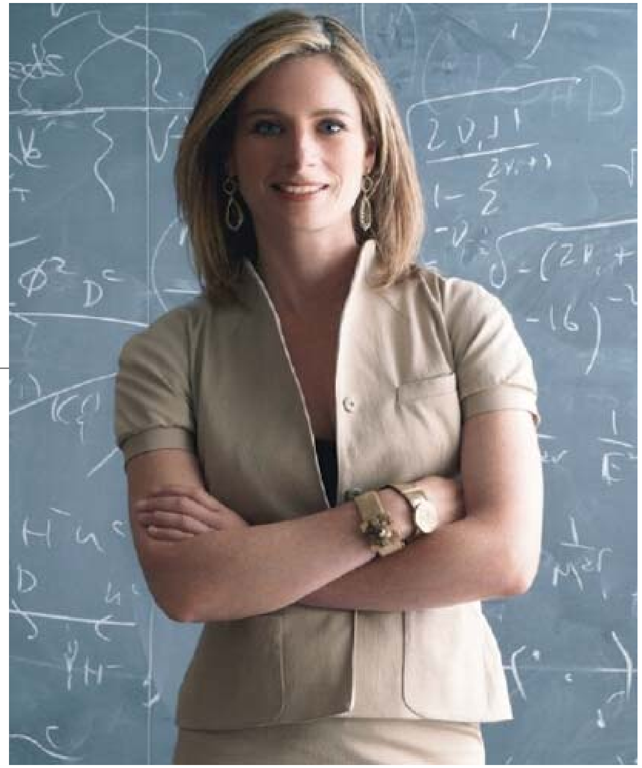

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in the Randall-Sundrum model, and the right structure of the **CKM matrix** are also obtained.

- **Tree-level FCNC** processes happen in the model, which is our main motivation to study flavor physics.

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Theoretical Preparation: General Set

- As mentioned before, we have had the space-time background with the metric,

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

$\phi = 0$, UV brane; $\phi = \pi$, IR brane.

- **Gauge group:**

$$SU(3)_c \times SU(2)_V \times U(1)_Y$$

- **5D Fields:**

Scalar SU(2) doublet: **$\Phi(x, \phi)$;**

Gauge fields: W_N^i, B_N, i = 1, 2, 3, N = 0, 1, 2, 3, ϕ;

Fermion fields: $\binom{U}{D}$, **u, d,** $\binom{\nu}{E}$, **e , (ν).** (each representing 3 generations)

Theoretical Preparation: $5\text{D} \Longrightarrow 4\text{D}$

- Having the action for the 5D theory at hand,

$$S = \int dx^4 \int_{-\pi}^{\pi} d\phi \, \sqrt{-G} \; \mathcal{L}[\mathbf{F}(\mathbf{x},\boldsymbol{\phi})],$$

we need to integrate over the 5th dimension to obtain the 4D effective theory.

- **Kaluza-Klein decomposition:**

$$F(x,\phi) = \sum_{n=0}^{\infty} f_n(x) \, \chi_{\boldsymbol{f}}^{(\boldsymbol{n})}(\phi)$$

The profiles $\chi_{\boldsymbol{f}}^{(\boldsymbol{n})}(\phi)$ can be obtained by solving the EoMs. $f_n(x)$ are 4D fields.

n = 0: $f_0(x)$ correspond to the **SM particles**;

n > 0: $f_n(x)$ are **KK excitations** of the SM particles, with the lowest masses $\sim$ **2.45**$\boldsymbol{M_{KK}}$.

Theoretical Preparation: $5\text{D} \Longrightarrow 4\text{D}$

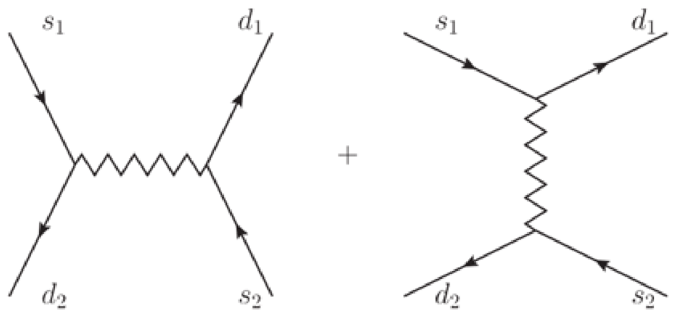
- **Interaction terms (Feynman rules):**

$$\mathcal{L} \ni \sum_{m,n,l} \int_{-\pi}^{\pi} d\phi\, g\, \bar{f}_m(x) f_n(x) V_l(x) \chi_f^{(m)}(\phi) \chi_f^{(n)}(\phi) \chi_V^{(l)}(\phi)$$

$$\Longrightarrow \bar{f}_m(x) f_n(x) V_l(x): \quad g \int_{-\pi}^{\pi} d\phi\, \chi_f^{(m)}(\phi) \chi_f^{(n)}(\phi) \chi_V^{(l)}(\phi)$$

- **4-fermion interaction (Wilson coefficients):**

The RS corrections to the Wilson coefficients are obtained by summing over the contributions from all possible mediate propagators, including KK excitations of the scalars and gauge bosons.



$V_n(x)$: n = 1, 2, 3, …

$S_n(x)$: n = 1, 2, 3, …

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Constraints from the oblique parameters: S, T & U

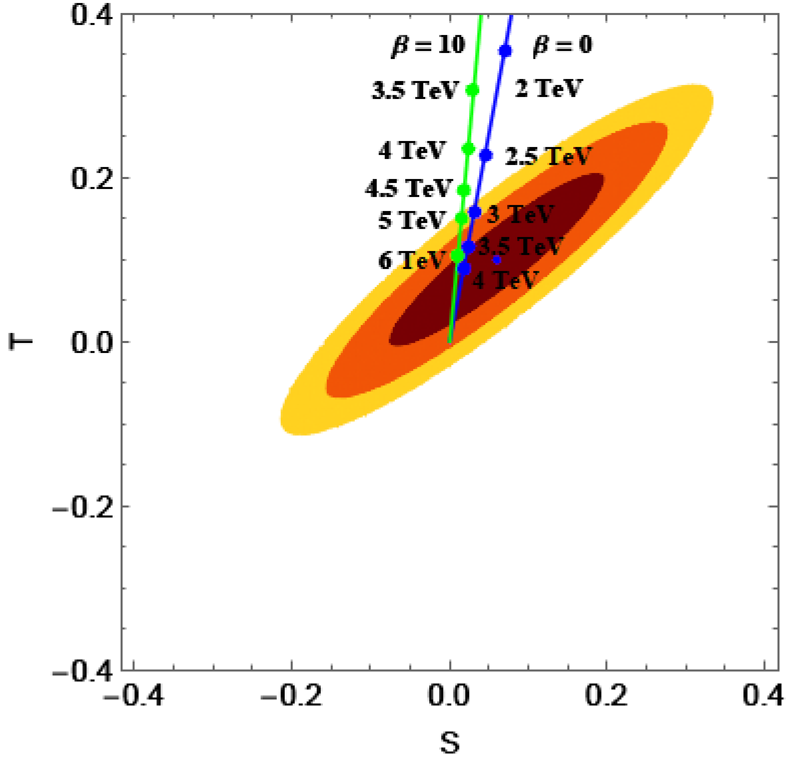
$$S = \frac{2\pi v^2}{M_{KK}^2}\left(1 - \frac{1}{(2+\beta)^2} - \frac{1}{2L}\right),$$

$$T = \frac{\pi v^2}{2 c_W^2 M_{KK}^2}\,\frac{2L(1+\beta)^2}{(2+\beta)(3+2\beta)}, \quad U = 0.$$

Gfitter [arXiv:1407.3792]:
$S = 0.06 \pm 0.09$,
$T = 0.10 \pm 0.07$,
with fixed $U = 0$.

$\Downarrow$

M_{KK} > 5 TeV, with β = 10;
M_{KK} > 3 TeV, with β = 0.



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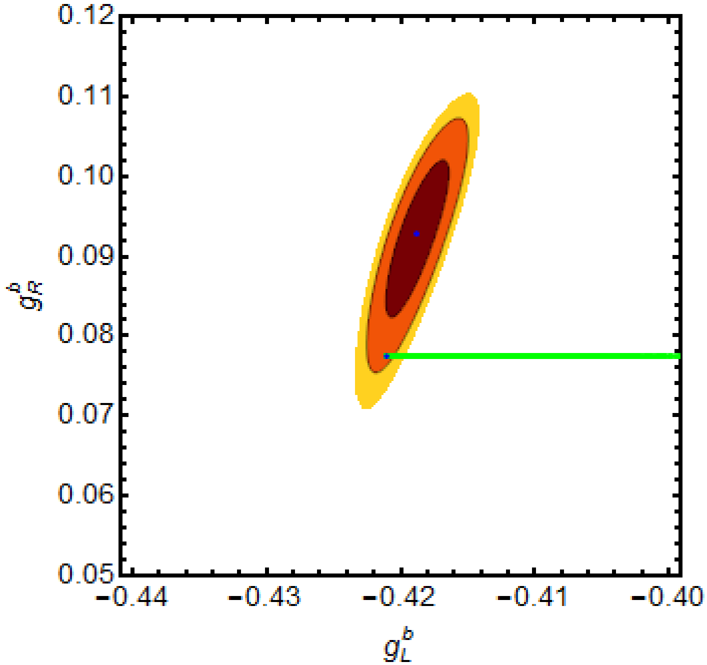
Constraints from Zbb couplings

The left- and right-handed $Z^0\bar{b}b$ couplings, g_L^b and g_R^b, are constrained by three pseudo observables at Z^0 pole,

R_b^0: $\Gamma(Z^0 \to \bar{b}b)$ / $\Gamma(Z^0 \to \text{hadrons})$;
A_b : the left-right forward-backward asymmetry;
$A_{FB}^{0,b}$: the forward-backward asymmetry.

The have been precisely measured by the Z^0 pole experiments, [arXiv: hep-ex/0509008]

$$R_b^0 = 0.21629 \pm 0.00066,$$
$$A_b = 0.923 \pm 0.020,$$
$$A_{FB}^{0,b} = 0.0992 \pm 0.0016.$$



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Right-handed Wtb coupling

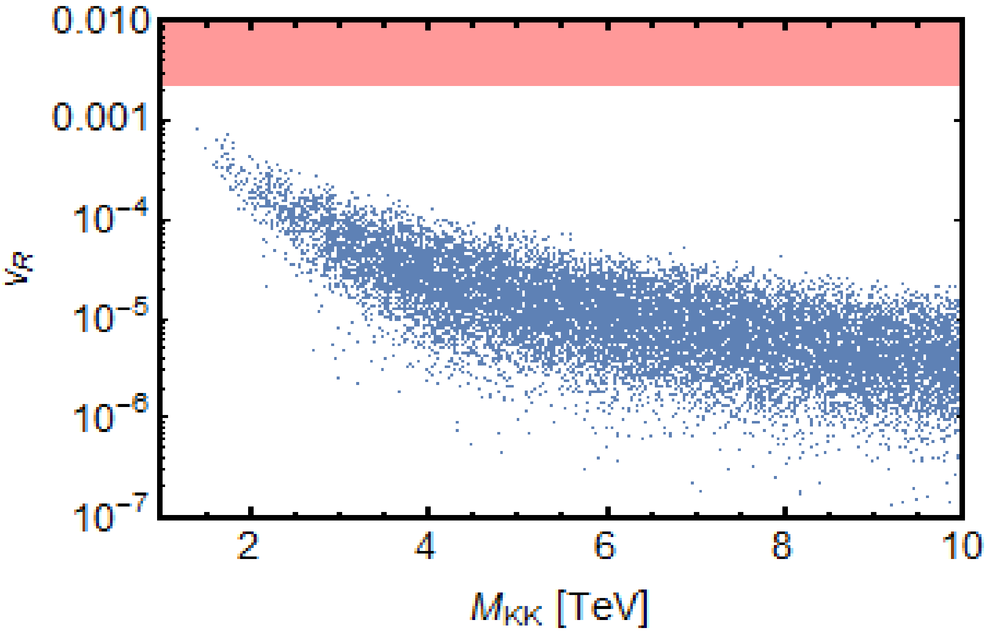
The right-handed Wtb coupling can be regarded as the right-handed CKM matrix element, $(\boldsymbol{V_R})_{33}$, multiplied by the weak coupling $\boldsymbol{g}$.

- Direct constraint from $t \to W^+ b$

$(\boldsymbol{V_R})_{33} \in$ [-0.1, 0.1],
[CMS, arXiv:1410.1154]

- Indirect constraint from $b \to s\gamma$

$(\boldsymbol{V_R})_{33} \in$ [-0.0008, 0.0022],
[arXiv:0802.1413]



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Rare decay: $t \to Z^0 c$

Suppressed by the GIM mechanism, the SM prediction for the branching ratio of the rare decay $t \to Z^0 c$ is $\sim \mathcal{O}(10^{-14})$, [hep-ph/0409342].

- Present limit at 95% C.L.,

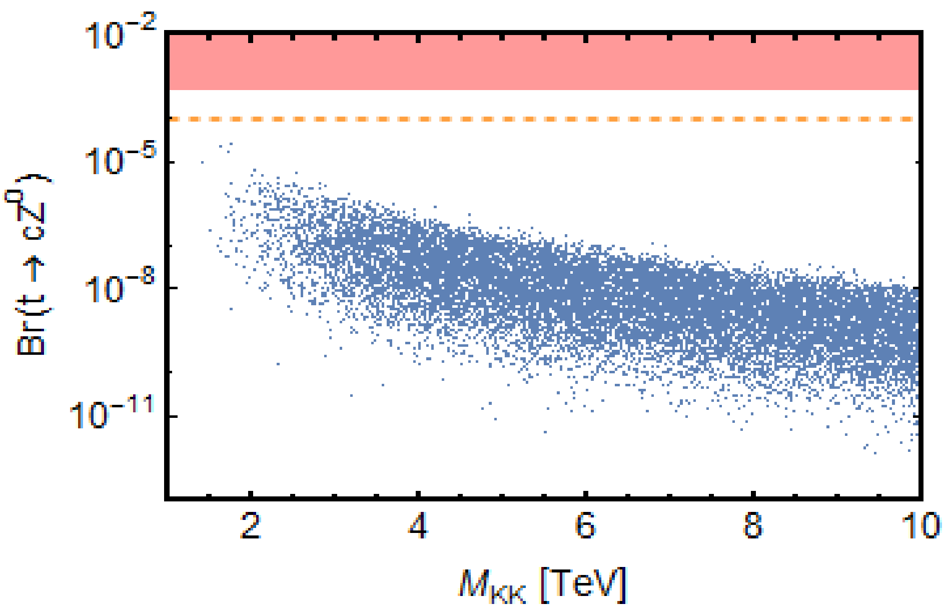
$\text{Br}(t \to Z^0 c) < 0.05\%$

[CMS, arXiv:1312.4194]

- Expected limit from future LHC,

$\text{Br}(t \to Z^0 c) < 10^{-4}$

[arXiv:0802.1413]



Rare decay: $t \to Hc$

The SM prediction for the branching ratio of the rare decay $t \to Hc$ is of the order $\mathcal{O}(10^{-15})$, [hep-ph/0409342].

- Present limit at 95% C.L.,

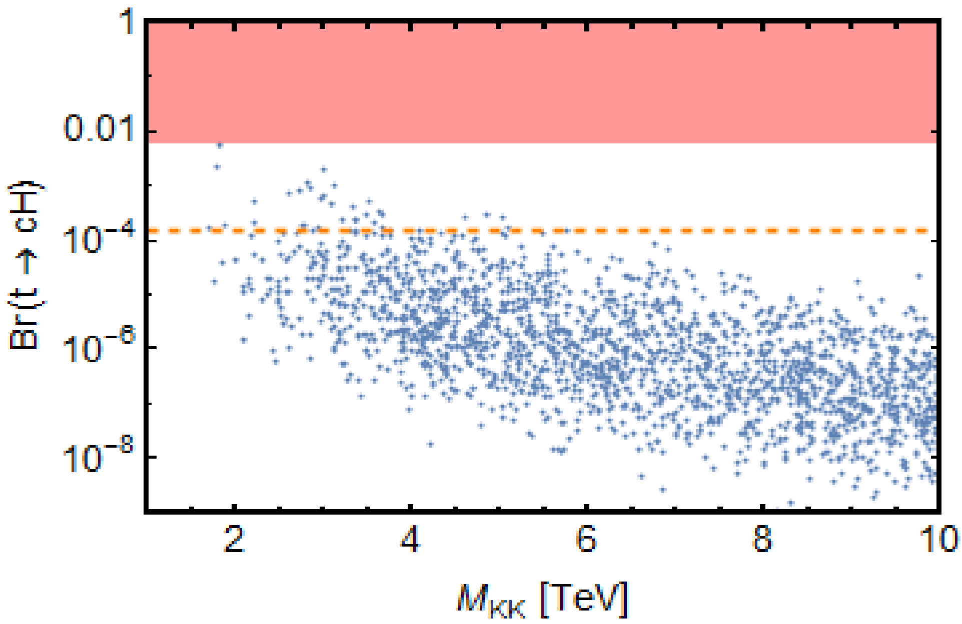
  Br($t \to Hc$) < 0.56%

  [arXiv:1410.8793]

- Expected limit from future LHC,

  Br($t \to Hc$) < 1.5×10^{-4}

  [Atlas: ATL-PHYS-PUB-2013-012]



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K^0-$\bar{K}^0$ mixing

The mixing effect of the K^0-$\bar{K}^0$ system is characterized by the observable,

$$\boldsymbol{\varepsilon_K \equiv \mathcal{A}[K_L \to (\pi\pi)_{I=0}]/\mathcal{A}[K_S \to (\pi\pi)_{I=0}]},$$

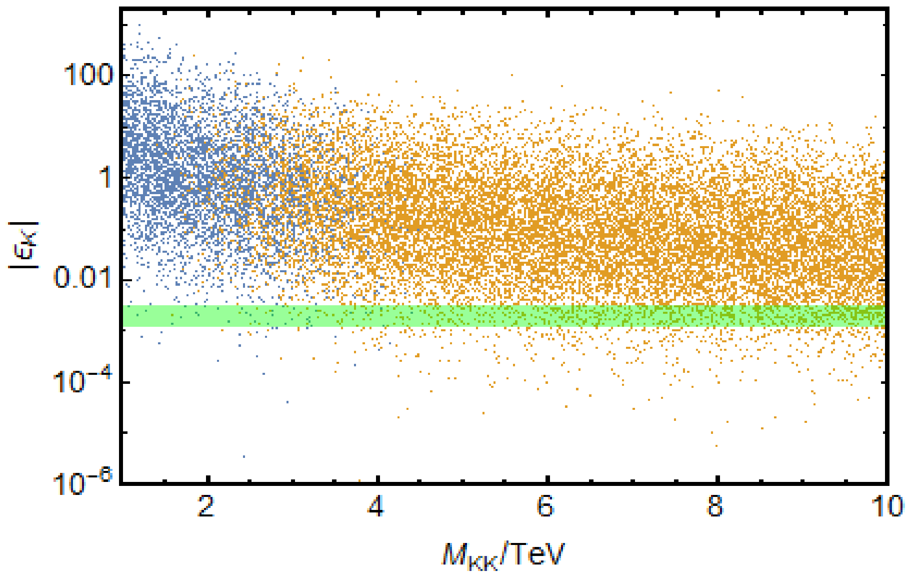
which has been precisely measured and the world average [PDG2014] is

$$\boldsymbol{|\varepsilon_K| = (2.228 \pm 0.011) \times 10^{-3}}.$$

The SM prediction for $|\varepsilon_K|$ is

$$\boldsymbol{|\varepsilon_K| = (2.1 \pm 0.4) \times 10^{-3}}.$$

As shown in the right figure, most of the RS points are ruled out by the constraint from $|\varepsilon_K|$.



B_d^0-$\bar{B}_d^0$ mixing

In the B_d^0-$\bar{B}_d^0$ mixing system, we study the following observables,

$\Delta\Gamma_d$: the width difference between the mass eigenstates;
A_{SL}^d: the CP asymmetry in the semileptonic decays;
$S_{\psi K_S}$: the mixing induced CP asymmetry in $B_d \to \psi K_S$.

	Exp. results	SM predictions	RS predictions
$\Delta\Gamma_d/\Gamma_d$	0.001 ± 0.010	**[0.003, 0.005]**	**[0.003, 0.005]**
$S_{\psi K_S}$	0.676 ± 0.021	0.682 ± 0.019	**[0.58, 0.78]**
A_{SL}^d	-0.0015 ± 0.0017	**[-0.0006, -0.0004]**	**[-0.0015, 0.0003]**

B_s^0-$\bar{B}_s^0$ mixing

In the B_s^0-$\bar{B}_s^0$ mixing system, we study the following observables,

$\Delta\Gamma_s$: the width difference between the mass eigenstates;
A_{SL}^s: the CP asymmetry in the semileptonic decays;
$S_{\psi\Phi}$: the mixing induced CP asymmetry in $B_s \to \psi\Phi$.

	Exp. results	SM predictions	RS predictions
$\Delta\Gamma_s/\Gamma_s$	0.122 ± 0.009	[0.10, 0.14]	[0.11, 0.16]
A_{SL}^s	-0.0075 ± 0.0041	$[1.5, 2.6] \times 10^{-5}$	[-0.0043, 0.0064]
$S_{\psi\Phi}$	0.015 ± 0.035	[0.0351, 0.0377]	[-0.09, 0.13]

D^0-$\bar{D}^0$ mixing

In the D^0-$\bar{D}^0$ mixing system, we study the observable,

$S^D_{\Phi K_S}$, the mixing induced CP asymmetry in $D \to \Phi K_S$.

	SM predictions	RS predictions
$S^D_{\Phi K_S}$	[-0.05, 0.24]	[-0.012, 0.012]

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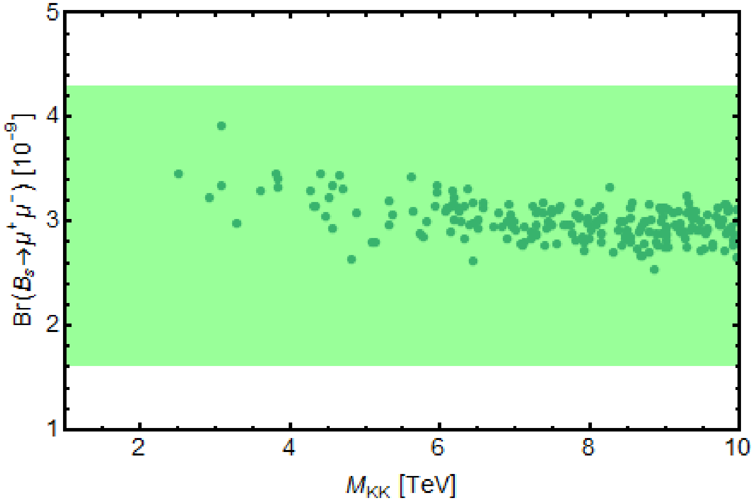
B meson rare decays

- CMS and LHCb measurements,

$$\mathrm{Br}(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathrm{Br}(B_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

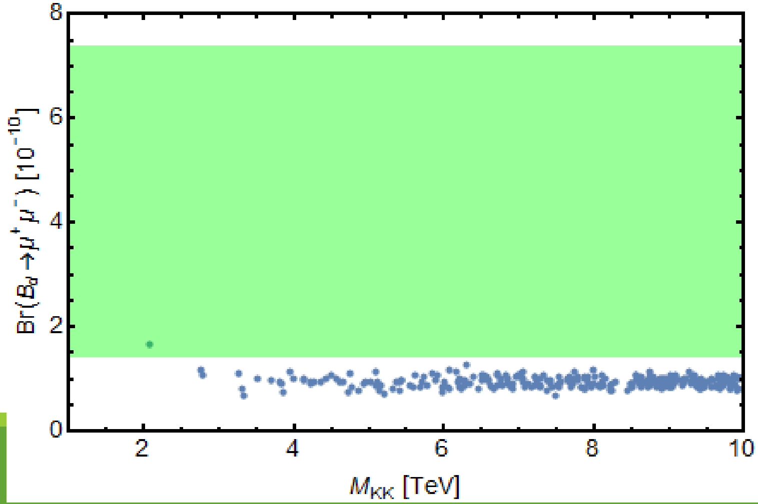
[arXiv:1411.4413]



- SM predictions,

$$\mathrm{Br}(B_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathrm{Br}(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

[arXiv:1311.0903]



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Conclusion

- In the extra dimensional extension of the Standard Model where all the fields propagate in the 5D space-time, the **gauge hierarchy problem** is solved. Simultaneously, the right **hierarchies of fermion masses and mixing** are generated.

- Because of the KK excitations of the gauge bosons and scalars, there are **tree-level FCNC** processes in the model. Therefore, fruitful phenomena could be observed in flavor physics.

- The RS effects on the **STU** parameters, **Zbb** & **Wtb** couplings , $t \to Z^0 c$ & $t \to Hc$ decay, K^0-$\bar{K}^0$, B_d^0-$\bar{B}_d^0$, B_s^0-$\bar{B}_s^0$ and D^0-$\bar{D}^0$ mixing, and **B meson rare decays** are studied. Some deviation from the SM predictions is hopefully to be observed.

Outlook

- B meson semileptonic decays
- B meson non-leptonic decays
- vacuum stability
- collider phenomenology
- …

Thank you for the attention!!