Testing the Bulk Matter RS Model through Flavor-Violating Decays of Smuon and Scharm

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Introduction

- Origin of the Yukawa coupling hierarchy ?
- One solution :

"5D RS spacetime with matter fields in the bulk"

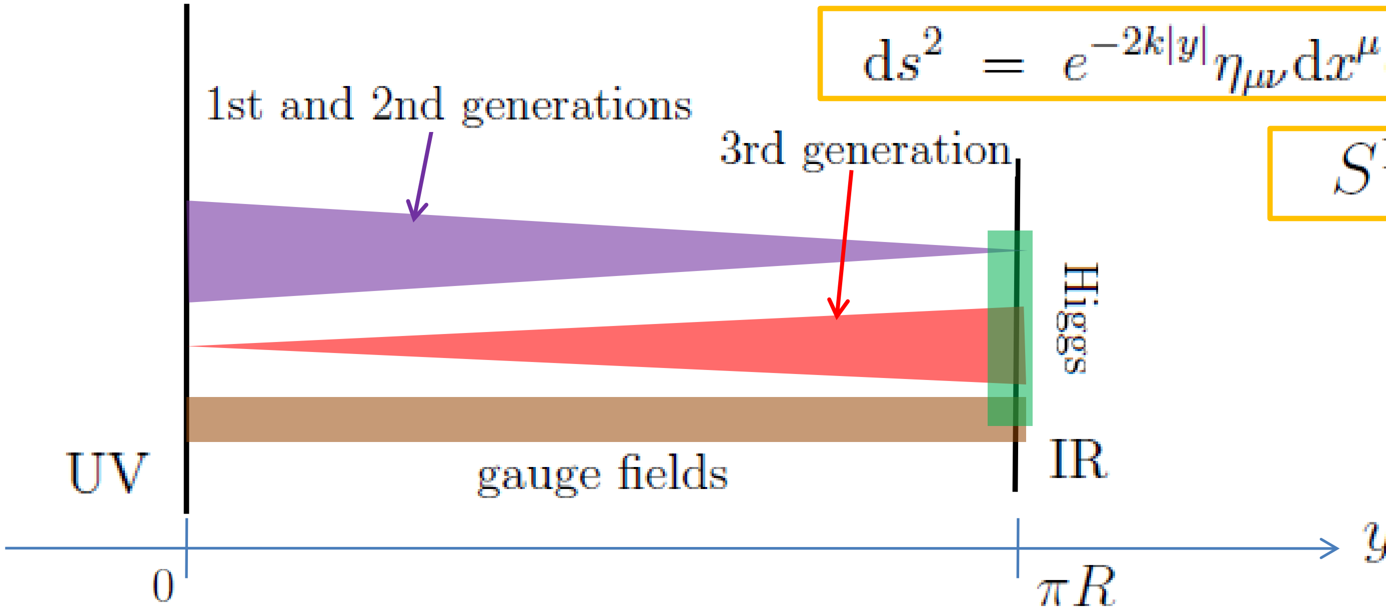
- The Kaluza-Klein scale of RS spacetime **need not be at TeV** if you want to explain the Yukawa hierarchy **only**.

- How can we confirm "the bulk matter RS model" if KK scale is far above TeV ?

If SUSY particles are accessible at colliders, we can do that by studying their **rare decays**.

Setup

Bulk Matter RS Model



$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

$$S^1/Z_2$$

- Matter and gauge fields in the bulk, Higgs on the IR brane.
- Each matter field has a 5D Dirac mass (c_i in unit of AdS curvature), which controls the field **localization** in 5D.
- ``Geometrical overlap" among two matter fields and Higgs is given by

$$\sqrt{\frac{1-2c_i}{2\{1-e^{-(1-2c_i)kR\pi}\}}}\sqrt{\frac{1-2c_j}{2\{1-e^{-(1-2c_j)kR\pi}\}}} \quad (c_i : \text{5D Dirac mass}, \ i,j : \text{flavor indices})$$

- ``Geometrical overlap factors'', $\sqrt{\frac{1-2c_i}{2\{1-e^{-(1-2c_i)kR\pi}\}}}$, give rise to the hierarchy of the Yukawa couplings.

Write $\alpha_i \equiv \sqrt{\frac{1-2c_{q\,i}}{2\{1-e^{-(1-2c_{q\,i})kR\pi}\}}}$ for SU(2) doublet quarks Q_i ,

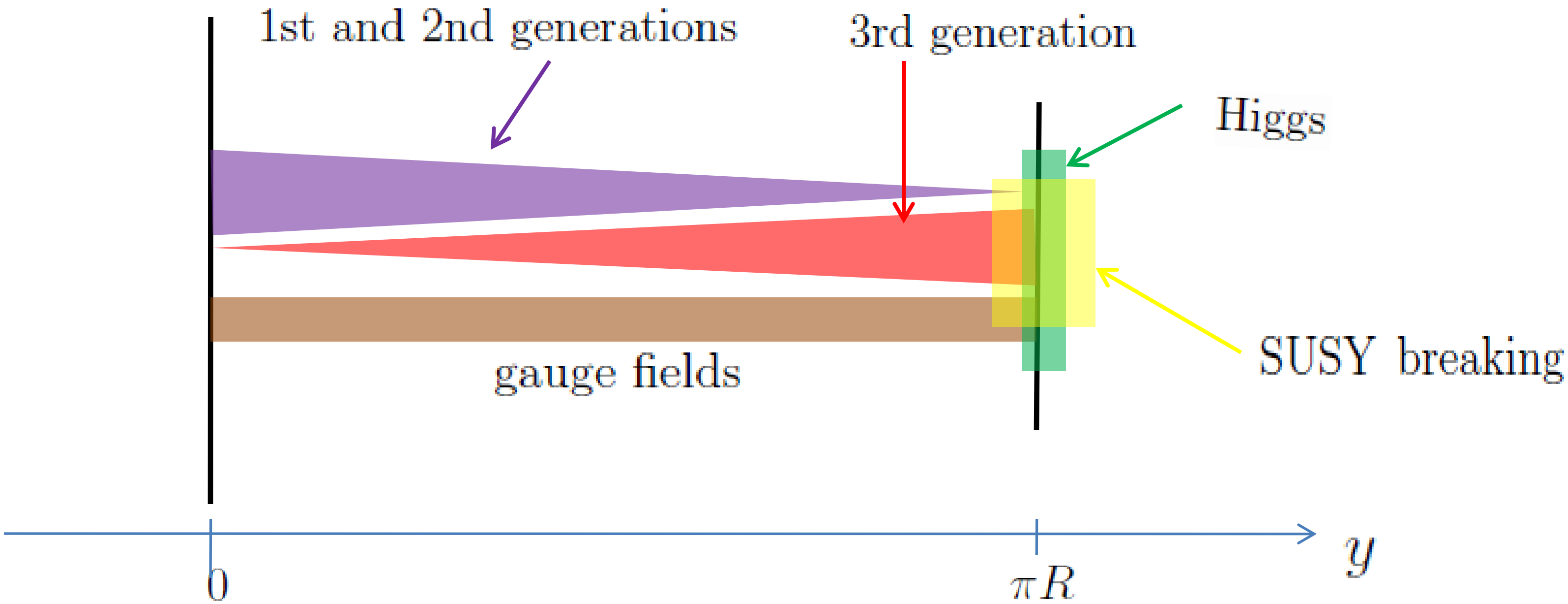
$\beta_i, \gamma_i, \delta_i, \epsilon_i$ for U_i, D_i, L_i, E_i .

- In an **arbitrary** flavor basis,

up-type quark Yukawa : $(Y_u)_{ij} \sim \beta_i \alpha_j$
down-type Yukawa : $(Y_d)_{ij} \sim \gamma_i \alpha_j$
charged lepton Yukawa : $(Y_e)_{ij} \sim \epsilon_i \delta_j$
neutrino Majorana mass : $(M_\nu)_{ij} \propto \delta_i \delta_j$

⇨ The magnitudes of $\alpha_i, \beta_i, \gamma_i, \delta_i, \epsilon_i$ are determined from the data on SM fermion masses, CKM and neutrinos.

SUSY Bulk Matter RS Model



- SUSY breaking sector on the IR brane.
- Gravity mediation for 1st and 2nd generation matter fields is geometrically suppressed. ➡ 5D sequestering
- Can add messenger fields.

➡ Hybrid of gravity mediation (on IR brane), gaugino mediation and (optional) gauge mediation.

Soft SUSY Breaking Terms

Two Scales of Soft Terms

I. Gravity mediation contributions

Gaugino mediation contributions

(Gaugino masses arise from contact terms, then their RG effects give rise to matter soft masses)

➡ The scale of these contributions is given by:

$$\sim \frac{|<F>|}{M_5 e^{-kR\pi}} \equiv M_X$$

F-term SUSY breaking

II . Gauge mediation contributions

➡ The typical scale of messenger mass determines the scale of soft terms from these contributions :

$$\sim \frac{1}{16\pi^2}\frac{|<F>|}{M_{mess}} \equiv M_G$$

Flavor Structure of Soft Terms

- Gravity mediation violates flavor.
- Gravity mediation arises from contact terms on IR brane.

➡ **Geometrical overlap factors, $\alpha_i, \beta_i, \gamma_i, \delta_i, \epsilon_i$, determine the magnitudes of gravity mediation contributions.**

$$(m_Q^2) \sim \alpha_i \alpha_j M_X^2, \quad (m_U^2) \sim \beta_i \beta_j M_X^2, \quad (m_D^2) \sim \gamma_i \gamma_j M_X^2,$$
$$(m_L^2) \sim \delta_i \delta_j M_X^2, \quad (m_E^2) \sim \epsilon_i \epsilon_j M_X^2;$$
$$(A_u)_{ij} \sim \beta_i \alpha_j M_X, \quad (A_d)_{ij} \sim \gamma_i \alpha_j M_X, \quad (A_e)_{ij} \sim \epsilon_i \delta_j M_X$$

- Gaugino mediation and gauge mediation generate flavor-universal terms only.

➡ **Gravity mediation contributions are detectable thru flavor-violating soft terms.**

Gravity Mediation vs. MFV

- Unfortunately, RG of Yukawa couplings also generate flavor-violating soft terms. (``Minimal Flavor Violation”)
- Want to distinguish Gravity mediation contributions from MFV contributions.

Magnitudes of MFV Contributions

- Take the basis where $(Y_u)_{ij}$ is diagonal.
- MFV contributions to $(m_U^2)_{ij},\ (A_u)_{ij}$ in this basis can be expressed in terms of α_i, β_i :

$$\begin{cases} (m_U^2)_{ij} \sim \beta_i(\alpha_i)^2(\alpha_j)^2\beta_j \max\{M_X, M_G\}^2, \\ (A_u)_{ij} \sim \beta_i(\beta_i)^2\alpha_j\, M_X \qquad . \end{cases}$$

⇨ MFV contributions to $(m_U^2)_{ij},\ (A_u)_{ij}$ may be much smaller than Gravity mediation contributions due to the extra geometrical factors.

- Similar arguments for $(m_D^2)_{ij},\ (A_d)_{ij},\ (m_E^2)_{ij},\ (A_e)_{ij}$.

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Experimental Test

- Gravity mediation contrubutions in the bulk matter RS model reflect the magnitudes of ``geometrical overlap factors”.
- These contributions may be distinguishable from MFV contributions if we focus on SU(2) singlet SUSY particles, U_i, D_i, E_i .

- Since gravity mediation violates flavor,
it induces **flavor-mixings in SUSY particle mass eigenstates**.

⇨ Focus on the mixing ratios in mass eigenstates.

SUSY Particle Flavor-mixings

- In general, when the mass matrix takes the form :

$$\begin{pmatrix} m_a^2 & \Delta m^2 \\ \Delta m^2 & m_b^2 \end{pmatrix}$$

with $|m_a^2 - m_b^2| >> 2|\Delta m^2|$,

the mixing ratios in the mass eigenstates become

$$|m_a^2 - m_b^2| \ : \ |\Delta m^2| \ , \qquad |\Delta m^2| \ : \ |m_a^2 - m_b^2| \quad .$$

- For example, the ratio of U_i component in ``almost U_j mass eigenstate" $(i > j)$ is given by $(\ \beta_j / \beta_i\ )$, the ratio of Q_i component is given by $(\ \beta_j \alpha_i\ v_u / |m_Q^2 - m_U^2|\ )$.

Outline of Testing the Model

- Consider a **lepton collider**.
- Tune the center-of-mass energy **between the thresholds** of SU(2) doublet and singlet sleptons (squarks), so that only SU(2) singlet sleptons (squarks) are pair-created on-shell.
- Study the pattern of the decay products.
- Estimate the ratios of ``main events” vs. ``rare events”. These correspond to the flavor-mixing ratios in sparticle mass eigenstates.

Assumption on the Mass Spectrum

- Assume

$$\tilde{H}_u, \tilde{H}_d \; > \; \tilde{g} \; > \; \tilde{q}_L \; > \; \tilde{q}_R$$
$$> \; \chi_1^\pm,\; \chi_2^0\,(\simeq \tilde{W}) \; > \; \chi_1^0\,(\simeq \tilde{B}) \; > \; \tilde{l}_L \; > \; \tilde{l}_R \; > \; \psi_{3/2} \; .$$

- Next-to-lightest SUSY particle = Stau.

Two Channels for observing gravity mediation contributions and testing bulk matter RS model.

Channel – I : Smuon Rare Decay

- Create ``almost **SU(2) singlet smuon** mass eigenstate”.
- It mainly decays into SM muon + tau + NLSP stau :

$$ee \;\rightarrow\; \tilde{\mu}_R\, \tilde{\mu}_R \;\rightarrow\; \mu\; \tau\; \tilde{\tau}_1\; \mu\; \tau\; \tilde{\tau}_1$$

- Due to small **stau component**, it also decays into two SM taus + NLSP stau :

$$ee \;\rightarrow\; \tilde{\mu}_R\, \tilde{\mu}_R \;\rightarrow\; \tau\; \tau\; \tilde{\tau}_1\; \mu\; \tau\; \tilde{\tau}_1$$

- The branching ratio of the latter event is predicted to be

$$(\,\epsilon_2 \,/\, \epsilon_3\,)^2 \;\sim\; (\,m_\mu \,/\, m_\tau\,)^2 \;\sim\; 0.004 \qquad .$$

Channel – II : Scharm Rare Decay

- Create ``almost **SU(2) singlet scharm** mass eigenstate".
- It mainly decays into SM charm + neutralino (≈Bino), which decays into SM leptons + NLSP stau :

$$ee \ \rightarrow \ \tilde{c}_R \, \tilde{c}_R \ \rightarrow \ c \, \chi_1^0 \, c \, \chi_1^0 \ \rightarrow \ (c\text{–jet}) \ (c\text{–jet}) \ (\text{leptons}) \ \tilde{\tau}_1 \ \tilde{\tau}_1$$

- Due to small s-top component, it also decays into SM top + neutralino :

$$\begin{aligned} ee \ &\rightarrow \ \tilde{c}_R \, \tilde{c}_R \ \rightarrow \ t \, \chi_1^0 \, c \, \chi_1^0 \\ &\rightarrow \ (\text{top decay products}) \ (c\text{–jet}) \ (\text{leptons}) \ \tilde{\tau}_1 \ \tilde{\tau}_1 \end{aligned}$$

- The branching ratio of the latter is predicted to be

$$(\ \beta_2 \ / \ \beta_3 \ )^2 \ \sim \ \left(\frac{1}{\lambda^2} \frac{m_c}{m_t} \right)^2 \ \sim \ 0.02 \quad .$$

Conclusions

- It is possible to test the bulk matter RS model even if KK scale is far above TeV, provided SUSY particles are accessible.
- Flavor structure of gravity mediation contributions reflects the ``geometrical overlap factors” that give rise to the Yukawa coupling hierarchy.
- This structure can be observed through rare decays of SUSY particle mass eigenstates.
- ``almost SU(2) singlet smuon mass eigenstate” decaying into SM tau, and
  ``almost SU(2) singlet scharm mass eigenstate” decaying into SM top are good channels for future lepton colliders.