MSSM
in the Bulk of RS Spacetime

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Contents

- Introduction
- Setup
- SUSY breaking mass spectrum
- Numerical analysis on mass spectrum
- Summary and outlook

Introduction

Basic Structure

- Consider 5D Minimal SUSY Standard Model on Randall-Sundrum background.
- RS Kaluza-Klein scale is at an intermediate scale.
- **SUSY** solves the **gauge hierarchy** problem.
  RS spacetime naturally explains the **Yukawa coupling hierarchy**.

- SUSY breaking soft mass comes from two origins :
  Contact terms on IR brane ("Gravity Mediation")
  RG effects of gaugino mass ("Gaugino Mediation")

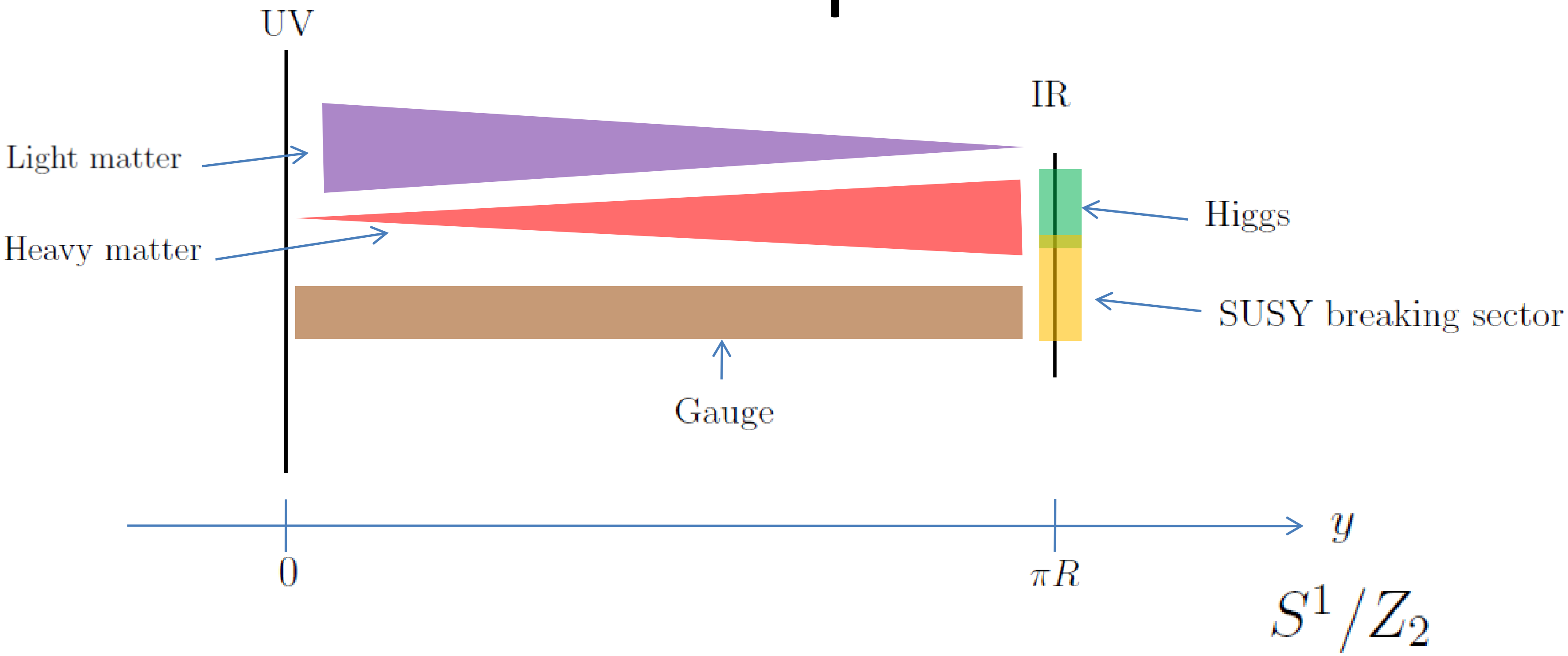
Features

- The same extradimensional sequestering controls
  Yukawa coupling hierarchy and
  Gravity mediation contribution to matter soft mass.
- It may be possible to reveal the **extradimensional origin of Yukawa hierarchy** by observing **Flavor-Violating parts of matter soft mass.**

coming from gravity mediation

Setup

Setup



- Higgs and SUSY breaking sector : on IR
- Matter and Gauge superfields : in the Bulk
- Zero-modes of 3rd generation : lean towards IR.
  Zero-modes of 1st generation : lean towards UV.

5D Profiles of Superfields

- 5D chiral superfield Lagrangian :

$$S_{5D\,chiral} = \int \mathrm{d}y \int \mathrm{d}^4 x e^{-4k|y|} \Big[\int \mathrm{d}^4\theta e^{2k|y|} \; (\Phi_i^\dagger e^{-V} \Phi_i \; + \; \Phi_i^c e^{V} \Phi_i^{c\dagger}) \\ + \int \mathrm{d}^2\theta e^{k|y|} \; \Phi_i^c \{\partial_y - \chi/\sqrt{2} - (3/2 - \overset{\boxed{\text{5D bulk mass}}}{c_i})k\}\Phi_i \; + \; \mathrm{h.c.} \Big]$$

Zero-mode profile : $f_i(y) \;\propto\; e^{(c_i - 1/2)k|y|}$

- 5D gauge superfield

Zero-mode profile : $f(y) \;\propto\; 1$

Yukawa couplings

- For MSSM matter fields, $Q_i,\ U_i,\ D_i,\ L_i,\ E_i$, denote their **overlaps with IR brane,** $f_i(\pi R)\ \propto\ e^{(c_i-1/2)k\pi R}$, as $\alpha_i,\ \beta_i,\ \gamma_i,\ \delta_i,\ \epsilon_i \quad (i:\ \text{flavor index})$

➡ have exponential hierarchy with $c \sim O(1)$.

- 4D Yukawa matrices take the form :

$$\left\{ \begin{array}{lcl} (Y_{4D\,u})_{ij} & = & (y_{5D\,u})_{ij}\ \beta_i\ \alpha_j \\ (Y_{4D\,d})_{ij} & = & (y_{5D\,d})_{ij}\ \gamma_i\ \alpha_j \\ (Y_{4D\,e})_{ij} & = & (y_{5D\,e})_{ij}\ \epsilon_i\ \delta_j \end{array} \right.$$

$\boxed{O(1)}$

Eigenvalues : $\sim \beta_1\alpha_1,\ \ldots\ ,\ \gamma_1\alpha_1,\ \ldots\ ,\ \epsilon_1\delta_1,\ \ldots$

CKM matrix takes the form :

$$\sim \begin{pmatrix} 1 & \alpha_1/\alpha_2 & \alpha_1/\alpha_3 \\ \alpha_1/\alpha_2 & 1 & \alpha_2/\alpha_3 \\ \alpha_1/\alpha_3 & \alpha_2/\alpha_3 & 1 \end{pmatrix}$$

Neutrino Mass

- Neutrino mass may arise from higher dim. operators on IR brane or from seesaw.
- Whichever is the case, neutrino mass arises from the term :

$$W \supset \underbrace{(y_{5D\nu})_{ij}}_{O(1)} \delta_i \delta_j \frac{L_i H_u L_j H_u}{\Lambda}$$

and we have

$$(M_\nu)_{ij} \sim \delta_i \delta_j$$

in the basis of charged lepton mass eigenstate.

Comparison with Data (Quark)

- From Top Yukawa, $\beta_3\alpha_3 \ \sim \ 1$. ➡ $\alpha_3 \sim 1, \quad \beta_3 \sim 1$
- From observed CKM matrix, we have

$\alpha_1 \sim \lambda^3, \ \ \alpha_2 \sim \lambda^2, \ \ \alpha_3 \sim 1$ with $\lambda = 0.22$.

- From observed fermion masses, we have

$$\beta_1 \sim \frac{1}{\lambda^3}\frac{m_u}{v_u}, \quad \beta_2 \sim \frac{1}{\lambda^2}\frac{m_c}{v_u}, \ \ \ldots\ldots.$$

Comparison with Data (Lepton)

- Since the neutrino mass matrix has democratic structure, we have

$$\delta_1 \sim \delta_2 \sim \delta_3 \ (\equiv \delta) \quad .$$

- From observed lepton masses, we have

$$\epsilon_1 \sim \frac{1}{\delta}\frac{m_e}{v_d} \ , \quad \epsilon_2 \sim \frac{1}{\delta}\frac{m_\mu}{v_d} \ , \quad \epsilon_3 \sim \frac{1}{\delta}\frac{m_\tau}{v_d} \quad .$$

SUSY Breaking Mass Spectrum

Overview

- At KK scale, no field propagates in the bulk.

⇒ SUSY breaking mass arises from **contact terms on IR brane**.

- Below KK scale, fields propagate in the bulk.

⇒ SUSY breaking effects are mediated by radiative corrections in the bulk, especially by **renormalization group contributions**.

- μ term arises only from SUSY breaking effects.

(Giudice-Masiero mechanism)

At KK Scale

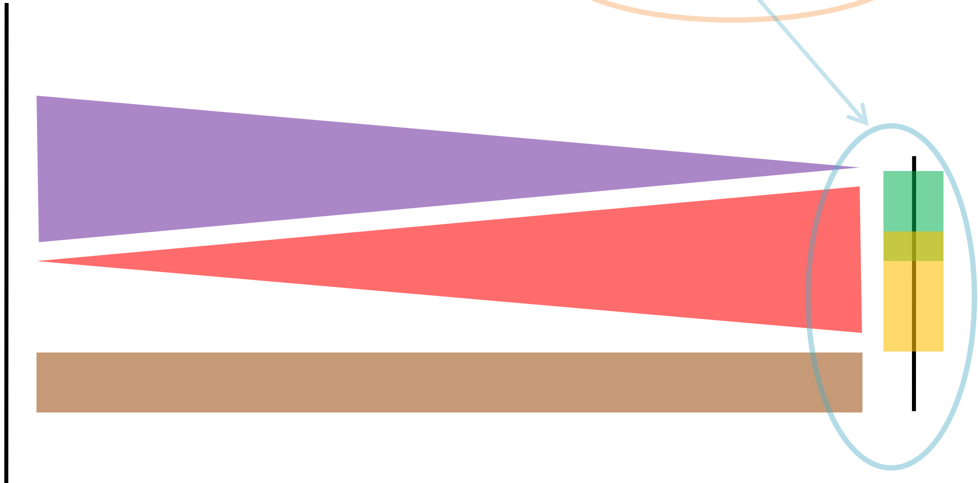
- SUSY breaking terms simply arise from higher dim. operators on IR brane.
- They are proportional to their resp. **overlaps with IR brane.**

M_X : typical SUSY breaking scale

Gaugino mass : $M^a_{1/2} \sim M_X$

Matter soft mass : $(m^2_Q)_{ij} \sim \alpha_i \alpha_j M^2_X$, $(m^2_U)_{ij} \sim \beta_i \beta_j M^2_X$, …

A-terms : $A_{u\,ij} \sim \beta_i \alpha_j M_X + \boxed{(Y_{4Du})_{ij} M_X}$ ← from Higgs F-terms



At Low Energies

- Low-energy spectrum is calculable by solving **MSSM RGE** with the initial condition in the previous slide.
- In particular, RG of gauginos generates large diagonal soft mass of matter sparticles,

  (hence the name “gaugino mediation”)

  which suppresses flavor-violating effects of SUSY breaking terms.

Gravity Mediation vs. Minimal Flavor Violation

- RG of Yukawa couplings also induces flavor off-diagonal soft mass of SU(2) doublet sparticles. (Minimal flavor violation (MFV))

1. For doublet sparticles, GM effects surpass MFV effects, as is shown below :

$$(Y_d^\dagger Y_d)_{ij} \sim \sum_k \alpha_i \beta_k \beta_k \alpha_j \lesssim \alpha_i \alpha_j$$

$$\rightarrow \frac{1}{16\pi^2} (Y_d^\dagger Y_d)_{ij}\, M_X^2\, \overset{\overset{\text{MFV}}{\swarrow}}{\ln}(\Lambda_{KK}/M_Z) < \overset{\overset{\text{GM}}{\downarrow}}{\alpha_i \alpha_j\, M_X^2}$$

⇒ It is sufficient to consider only GM effects.

2. For singlet sparticles, only GM effects exist.

⇒ Flavor-violating **singlet** soft mass is unique to our model.

LSP and NLSP

- LSP is gravitino with mass :

$$m_{3/2} \sim \mathrm{TeV} \times (\Lambda_{KK}/M_P)$$

- NLSP mostly consists of singlet sleptons.
  Its flavor composition is characteristic to the model.
  (as we will see later)

Numerical Analysis

Purpose of Analysis

To numerically check that the model gives realistic mass spectra evading experimental constraints on flavor.

Calculating Mass Spectrum

- With the initial conditions below, we solved MSSM RGE to derive low energy spectrum.

$$
\begin{aligned}
M^a_{1/2} &= 4(g^a_4)^2\, M_X\,, & A_{uij} &= -M_X(Y_u)_{ij} + a_{uij}\,\beta_i\alpha_j M_X\,,\\
m^2_{H_u} = m^2_{H_d} &= M^2_X\,, & A_{dij} &= -M_X(Y_d)_{ij} + a_{dij}\,\gamma_i\alpha_j M_X\,,\\
(m^2_Q)_{ij} &= c_{Qij}\,\alpha_i\alpha_j M^2_X\,, & A_{eij} &= -M_X(Y_e)_{ij} + a_{eij}\,\epsilon_i\delta_j M_X\,,
\end{aligned}
$$

$$(\mathrm{Q},\ \alpha) \quad \rightarrow \quad (\mathrm{U},\beta),\ (\mathrm{D},\gamma),\ (\mathrm{L},\delta),\ (\mathrm{E},\epsilon)\ ,$$

- As we allow O(1) ambiguity of grav. med. terms, we fixed :

$$
\begin{aligned}
c_{*ij},\ a_{*ij} &= 1 \quad \text{for } i = j\ ,\\
c_{*ij},\ a_{*ij} &= 0.1 \quad \text{for } i \neq j\ .
\end{aligned}
$$

- The free parameters of mass spectrum are :

$$
\left\{
\begin{array}{l}
M_X \ \text{(typical SUSY breaking scale)}\\
\delta \ \text{(since we do not know the value of seesaw scale)}\\
\tan\beta
\end{array}
\right.
$$

with the condition $\epsilon_3 \leq 1 \ \Leftrightarrow\ \delta \geq \tan\beta(m_\tau/v)$.

Low-energy Constraints

- Of all low-energy experiments on flavor, $\mu \to e\gamma$ experiment most severely constrains the model because of flavor-universal δ_i s.
- It gives strong limits on

Flavor-violating A-term :

$$A_{e\,12} \sim \delta_1 \epsilon_2 M_X \sim \delta \epsilon_2 \, M_X \sim (m_\mu / v_d) \, M_X$$

Flavor-violating soft mass :

$$(m_L^2)_{12} \sim \delta_1 \delta_2 \, M_X^2 \sim \delta^2 \, M_X^2$$

Samples of Realistic Spectrum

- For various values of $(M_X,\ \delta,\ \tan\beta)$, we calculated mass spectrum and compared it with experimental bounds on m_h and $Br(\mu \to e\gamma)$.
  ($m_h \geq 114.4\ \mathrm{GeV}$, $Br(\mu \to e\gamma) \leq 1.2 \times 10^{-11}$)
- Table of realistic mass spectra below :

M_X (GeV)	800	1000	1000	1000	1000	1000	1000	1000	1000
$\tan\beta$	5	5	5	5	5	10	10	10	15
δ	0.05	0.05	0.1	0.15	0.3	0.1	0.15	0.2	0.15
m_h (GeV)	116	117	118	118	118	121	121	121	122
$Br_\mu \times 10^{12}$	11	4.6	5.0	5.5	11	5.7	7.5	10	9.4

- For smaller M_X / $\tan\beta$, the bound on m_h unsatisfied.
- For larger δ / $\tan\beta$, the bound on Br_μ unsatisfied.

General Consequences

1. We have $\boxed{Br(\mu \to e\gamma) \gtrsim 5 \times 10^{-12}}$ in this model.

⇐ The order of the flavor-violating A-term, $A_{e\,12}$, is fixed at $\sim (m_\mu/v_d)\, M_X$ and it induces $\mu \to e\gamma$ event.

⇐ Yukawa couplings and A-terms from grav. med. are rooted on the same 5D structure.

2. $\boxed{\epsilon_3 \sim 1 \quad = \text{“singlet stau localized towards IR”}}$ is favored.

⇐ Since δ s are flavor-universal, the bound on $(m_L^2)_{12}$ severely constrains δ . (Note that $\epsilon_3 \propto 1/\delta$)

(c.f. ϵ_1, ϵ_2 are resp. suppressed by $(m_e/m_\tau), (m_\mu/m_\tau)$.)

Signatures at LHC

- “General consequence 2” suggests that singlet slepton mass matrix is significantly distorted by gravity mediation.
- Unusual **selectron-like NLSP** is the case for sample spectra in the table.
- Rate of rare decay of NLSP (e.g. selectron-like NLSP decaying into tau) is predictable in our model.

Summary and Outlook

Summary and Outlook

- Studied 5D MSSM on warped background.
- 5D disposition of MSSM superfields provides a natural explanation to Yukawa hierarchy and a viable SUSY breaking mechanism (gaugino mediation + gravity mediation).
- Signatures of the model were discussed.

- Study on rare decay of **singlet scharm** and **smuon** at ILC will prove the model.