Measurement of Gravity Mediation Contribution through Flavor-Violating Decays of Smuon and Scharm

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Introduction

Overview of the Model

- Consider **Minimal SUSY Standard Model** in **5D Warped Spacetime**.
- SUSY solves the gauge hierarchy problem. Consider gauge/gaugino mediation + grav. med.
- 5D warped spacetime:

$$\mathrm{d}s^2 \;=\; e^{-k|y|}\eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu \;-\; \mathrm{d}y^2 \;, \quad \pi R \geq y \geq 0$$

provides a natural explanation to the fermion mass hierarchy through “5D disposition” of matter fields.

- Note: the IR scale of warped spacetime, $M_P e^{-kR\pi}$, need not be at TeV scale and is a free parameter.

Our Task

- Soft Mass of Supersymmetric matter particles :

$$(m^2)_{ij} = m^2_{flavor\ blind}\,\delta_{ij} + (m^2_{flavor\ violating})_{ij}$$

i, j : flavor index

radiative correction from gauge fields
gauge field RGE

Yukawa RGE
gravity mediation contribution

- Our task :
  Measure grav. med. Contribution in $(m^2_{flavor\ violating})_{ij}$.

Discover a unique pattern of Gravity mediation.

Study 5D disposition of matter superfields.

Review on SUSY Breaking Soft Mass

Soft Mass of SUSY Matter Particles

- Origin of Flavor-Blind mass :

gauge interaction with messenger fields (gauge med.)

RG effects from gaugino mass → $\mu\frac{d}{d\mu}(m^2)_{ij} \supset \frac{1}{16\pi^2}\delta_{ij}(g^a)^2 M^a_{1/2}$

- Origin of Flavor-Violating mass :

Planck-suppressed terms (grav. med.) → $\mathcal{L} \supset \int \mathrm{d}^4\theta\, c_{ij}\frac{X^\dagger X}{M_P^2}Q_i^\dagger Q_j + \int \mathrm{d}^2\theta\, a_{ij}\frac{X}{M_P}Q_i H_u U_j$

RG effects from Yukawa couplings ↓

$$\mu\frac{d}{d\mu}(m_q^2)_{ij} \supset \frac{1}{8\pi^2}\left\{ (Y_u^\dagger Y_u)_{ik}(m_q^2)_{kj} + (Y_d^\dagger Y_d)_{ik}(m_q^2)_{kj} + (Y_u^\dagger m_u^2 Y_u)_{ij} + (Y_d^\dagger m_d^2 Y_d)_{ij} + \ldots \right\}$$

Flavor Non-diagonal Soft Mass

- Take the basis where SM particles are in their mass eigenstates.
- Planck-suppressed terms (+ RG effects including them) intrinsically contain flavor non-diag. terms.
- For SU(2) doublets, Yukawa RG induces non-diag. terms $\sim \frac{1}{16\pi^2} \ln\left(\frac{\Lambda}{M_Z}\right) (Y^\dagger Y)_{ij}\, m_0^2$.

  (m_0^2 : typical soft mass scale ~ 100 GeV)
- For SU(2) singlets, Yukawa-RG-origined non-diag. terms are further suppressed by 1st or 2nd generation Yukawa and are given by

$$\sim \left\{\frac{1}{16\pi^2} \ln\left(\frac{\Lambda}{M_Z}\right)\right\}^2 (Y')_{ii}\, (Y^\dagger Y)_{ij}\, (Y'^\dagger)_{jj}\, m_0^2 \quad .$$

Review on 5D Warped Model and Yukawa Hierarchy

Extra-Dimensional Superfields

- Consider 5D warped spacetime (y : 5th dim.)

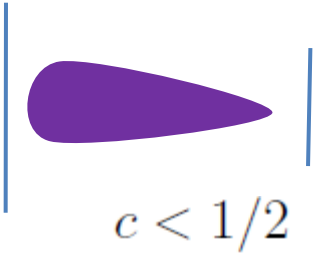
$$ds^2 = e^{-k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

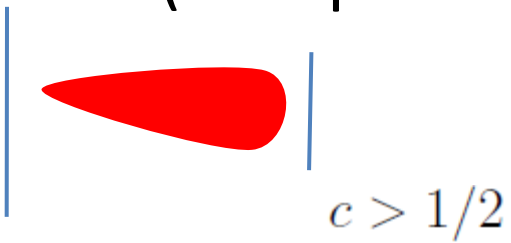
- Matter superfield depends on y .

  Massless mode has the following 5D disposition :

$$f(y) \propto e^{(c-1/2)k|y|}$$

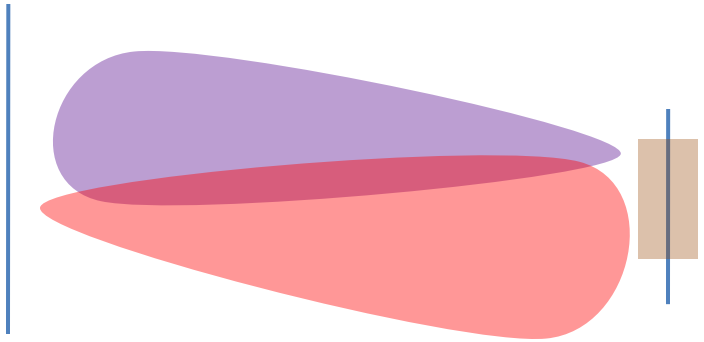
where c is 5D Dirac mass (new parameter).





Extra-Dimensional Superfields 2

- Extra-dimensional setup solves Yukawa hierarchy problem.



Higgs is put on the IR.

Yukawa coupling involving the **purple** field is **exponentially suppressed** with normal value of c , while one involving the **red** is **O(1)**.

⇒ Natural explanation to the fermion mass hierarchy.

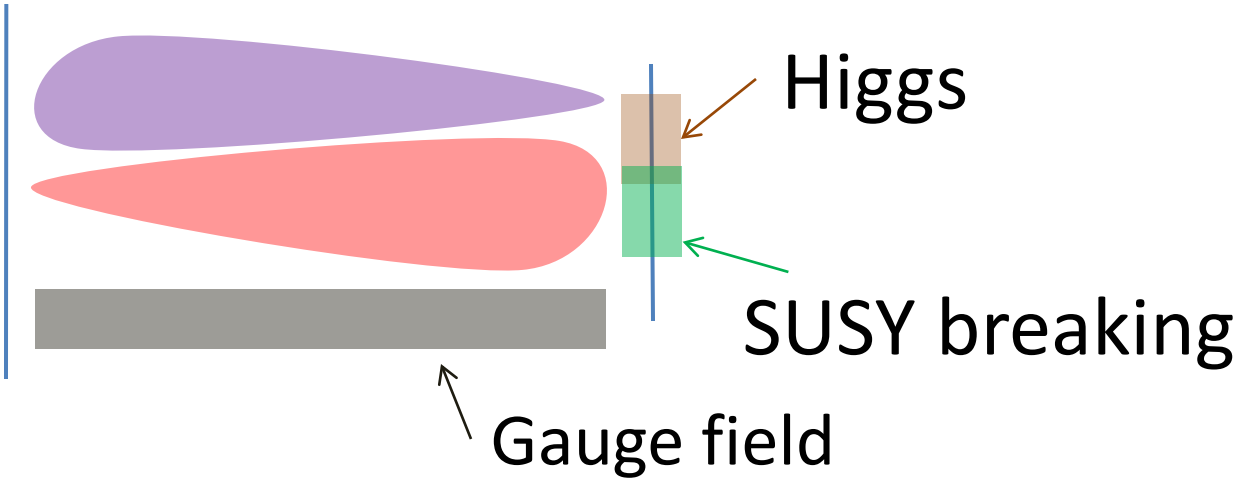
Details of the Model

Benchmark Model

- The simplest setup.
- Higgses and SUSY breaking source live on IR.
- No messenger fields.
  Gaugino mass arises from gravity mediation.
  RG effects of gaugino mass and gravity mediation generate matter soft mass.

  ⇒ ("Gaug**ino** Mediation")
- 5D disposition of matter superfields induces hierarchical structure of Yukawas and CKM matrix.

Basic structure



- The same 5D disposition of matter controls
  Yukawa and CKM matrix.
  Gravity mediation contribution to soft mass.

  ➡ Gravity-mediation-origined Flavor-Violating soft mass and Yukawa hierarchy are connected.

Lepton Sector

- First determine 5D disposition (y dependence) of matter superfields from Yukawa and neutrino data.
- Yukawa couplings : $O(1)$ overlap of Higgs and singlet 5D superfield; overlap of Higgs and doublet 5D superfield

$$(Y_{4D\,e})_{ij} = (y_{5D\,e})_{ij}\ \epsilon_i\ \delta_j$$

- Neutrino mixing matrix suggests $\delta_1 \sim \delta_2 \sim \delta_3\ (\equiv \delta)$.
  Hence $\epsilon_1 \sim \frac{1}{\delta}\frac{m_e}{v_d}$, $\epsilon_2 \sim \frac{1}{\delta}\frac{m_\mu}{v_d}$, $\epsilon_3 \sim \frac{1}{\delta}\frac{m_\tau}{v_d}$.
- **Flavor-Violating** Soft mass:

doublets $(m^2_{L\ flavor\ violating})_{ij} \sim \delta_i\delta_j\ m_0^2$ (+ large Yukawa RG effects)

singlets $(m^2_{E\ flavor\ violating})_{ij} \sim \epsilon_i\epsilon_j\ m_0^2$ (+ small Yukawa RG effects)

m_0^2 : typical soft mass scale $\sim$ 100 GeV

Our prediction on slepton soft mass.

Quark Sector

- Determine 5D disposition of squark superfields from Yukawa and CKM matrix.
- Yukawa couplings : $(Y_{4D\,u})_{ij} = (y_{5D\,u})_{ij}\ \beta_i\ \alpha_j$

  $(Y_{4D\,d})_{ij} = (y_{5D\,d})_{ij}\ \gamma_i\ \alpha_j$

  CKM matrix : $\sim \begin{pmatrix} 1 & \alpha_1/\alpha_2 & \alpha_1/\alpha_3 \\ \alpha_1/\alpha_2 & 1 & \alpha_2/\alpha_3 \\ \alpha_1/\alpha_3 & \alpha_2/\alpha_3 & 1 \end{pmatrix}$
- From the data on CKM matrix $\sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$ with $\lambda = 0.22$

  and estimation on top Yukawa $Y_{4D\,t} \sim O(1)$,

we have $\alpha_1 \sim \lambda^3, \quad \alpha_2 \sim \lambda^2, \quad \alpha_3 \sim 1$

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

Quark Sector 2

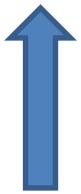
- FV Soft mass from gravity mediation :

doublet $(m^2_{Q\ flavor\ violating})_{ij} \sim \alpha_i \alpha_j\ m_0^2$ (+ large Yukawa RG effects)

up-type singlet $(m^2_{U\ flavor\ violating})_{ij} \sim \beta_i \beta_j\ m_0^2$

down-type singlet $(m^2_{D\ flavor\ violating})_{ij} \sim \gamma_i \gamma_j\ m_0^2$

(+ small Yukawa RG effects)



Our prediction on squark soft mass.

Constraints on the Model

- IR scale ~= Kaluza-Klein (KK) scale.

  Bound from $K^0 - \bar{K}^0$ mixing observation : $\Lambda_{IR} > 20\ \mathrm{TeV}$

  ➡ KK states are inaccessible at colliders.

- Lepton FV from slepton soft mass and A-terms.

  Bound from $\mu \to e\gamma$ experiment says :

  $\tan\beta \lesssim 10$ and $\epsilon_3 \sim 1$

  for realistic mass spectrum.

Measurements

Benchmark Spectrum

- Mass spectrum is based on "Gaug**ino** mediation" with warped spacetime.
- Take $\tan\beta = 5$.
- Take KK scale ~= IR scale ~= 10^{14} GeV.
- Gravitino mass : ~ 1 GeV ➡ the lightest SUSY particle.
- The next-to-lightest is singlet smuon $\tilde{\mu}_R$ or lighter stau $\tilde{\tau}_1$.

  (due to the ambiguity of grav. med. contribution)

  Its life time : $t_{3/2} \sim (m_{NLSP}/300\mathrm{GeV})^{-5} \times 1$ s.

  ➡ decays outside the detector.
- Take $\epsilon_3 = 1 \ (\Leftrightarrow \ \delta = \dfrac{v_d}{m_\tau})$ for 5D disposition of sleptons.

- Comparison of soft masses:

gluino > Higgsino > squarks > Wino > Bino

> doublet sleptons > singlet sleptons >> gravitino

What to Measure

- Ratio of flavor-violating decay of **singlet smuon**:

$$\frac{Br(\,\tilde{\mu}_R \to \tau\,\tilde{B}^* \to \tau\,\tau\,\tilde{\tau}_1\,)}{Br(\,\tilde{\mu}_R \to \mu\,\tilde{B}^* \to \mu\,\tau\,\tilde{\tau}_1\,)}$$ (if stau is lighter) or $$\frac{Br(\,\tilde{\mu}_R \to \tau\,\psi_{3/2}\,)}{Br(\,\tilde{\mu}_R \to \mu\,\psi_{3/2}\,)}$$ (if smuon is lighter)

- Ratio of flavor-violating decay of **singlet scharm**:

$$\frac{Br(\,\tilde{c}_R \to t\,\chi_1^0\,)}{Br(\,\tilde{c}_R \to c\,\chi_1^0\,)}$$

Reasons for these choices:

i. SU(2) singlet sparticles receive only suppressed flavor-violating RG effects.

⇒ Pure gravity mediation contribution is detectable.

ii. Smuon, scharm have only small singlet-doublet mixing:

$$\sim \underline{m_\mu}\,(A_0 - \mu\tan\beta)\,\tilde{\mu}_R\tilde{\mu}_L \quad , \quad \sim \underline{m_c}\,(A_0 - \mu\cot\beta)\,\tilde{c}_R\tilde{c}_L$$

iii. Smuon, scharm are predicted to have large FV soft terms:

smuon: $$\begin{cases} \sim \epsilon_2\epsilon_3\, m_0^2\, \tilde{\mu}_R^\dagger\tilde{\tau}_R \\ \sim \epsilon_2\delta_3\, v_d\, m_0\, \tilde{\mu}_R\tilde{\tau}_L \end{cases}$$

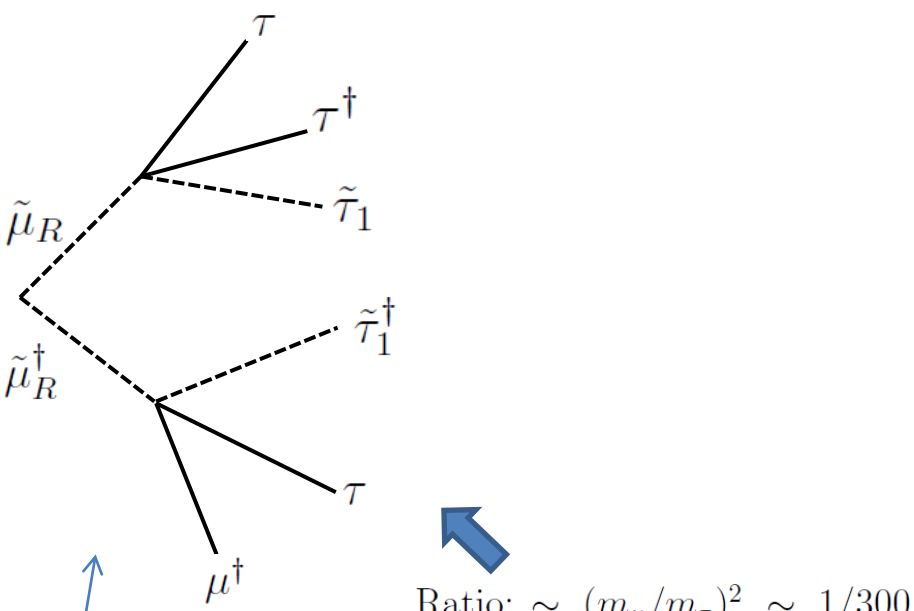
scharm: $$\begin{cases} \sim \beta_2\beta_3\, m_0^2\, \tilde{c}_R^\dagger\tilde{t}_R \\ \sim \beta_2\alpha_3\, v_u\, m_0\, \tilde{c}_R\tilde{t}_L \end{cases}$$

Events we focus on

- If smuon is NLSP and it decays only into gravitino, it is impossible to study the decay at colliders.

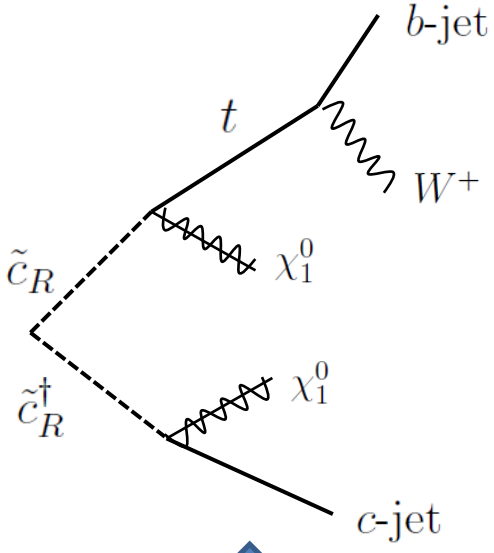
  (because of too long lifetime)

- Therefore we focus on two types of events:



(if smuon and stau have enough mass difference)

Ratio: $\sim (m_\mu/m_\tau)^2 \sim 1/300$



Ratio: $\sim (\lambda^{-2} m_c/m_t)^2 \sim 1/40$

Summary

Summary

- Gravity-Mediation-origined soft mass yields information on 5D disposition of matter fields.
- We focus on SU(2) singlet, 2nd generation sparticles.
- Their decays to 3rd generation SM particles are the key to study Gravity Mediation effects.

Can we solve the fermion mass hierarchy problem at ILC?