Sfermion Masses and Lepton Flavor Violation

part 1. 超対称性とフレーバー
part 2. Democratic Approach

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Part 1. 超対称性とフレーバー

質量の起源

- 電弱相互作用：ゲージ相互作用
  - 相互作用の強さはゲージ量子数（電荷）によって決まっている。 ⇐ 実験的に検証済み
- ゲージ粒子の質量
  - ゲージ対称性によりmassless。しかし、WボソンやZボソンはmassive
  - 対称性の自発的破れによって質量を獲得する

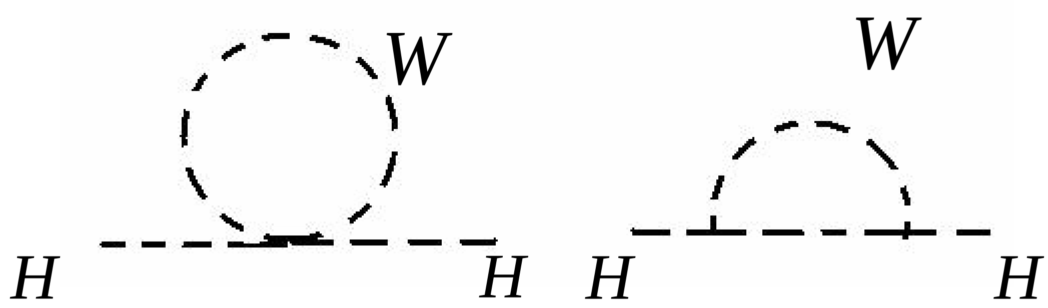
Higgs　機構

- **標準理論では**
  - Elementary Higgs field**を導入**
  - **対称性の自発的破れ**：　SU(2) doublet Higgs **が期待値を持つ**　→　W**や**Z**が質量を獲得**
  - **同時に、湯川相互作用により**quark**や**lepton**も質量を獲得！**　(economical!)

$$L_Y = y\psi_R \psi_L H$$

Higgs質量の量子補正

- **2次発散**

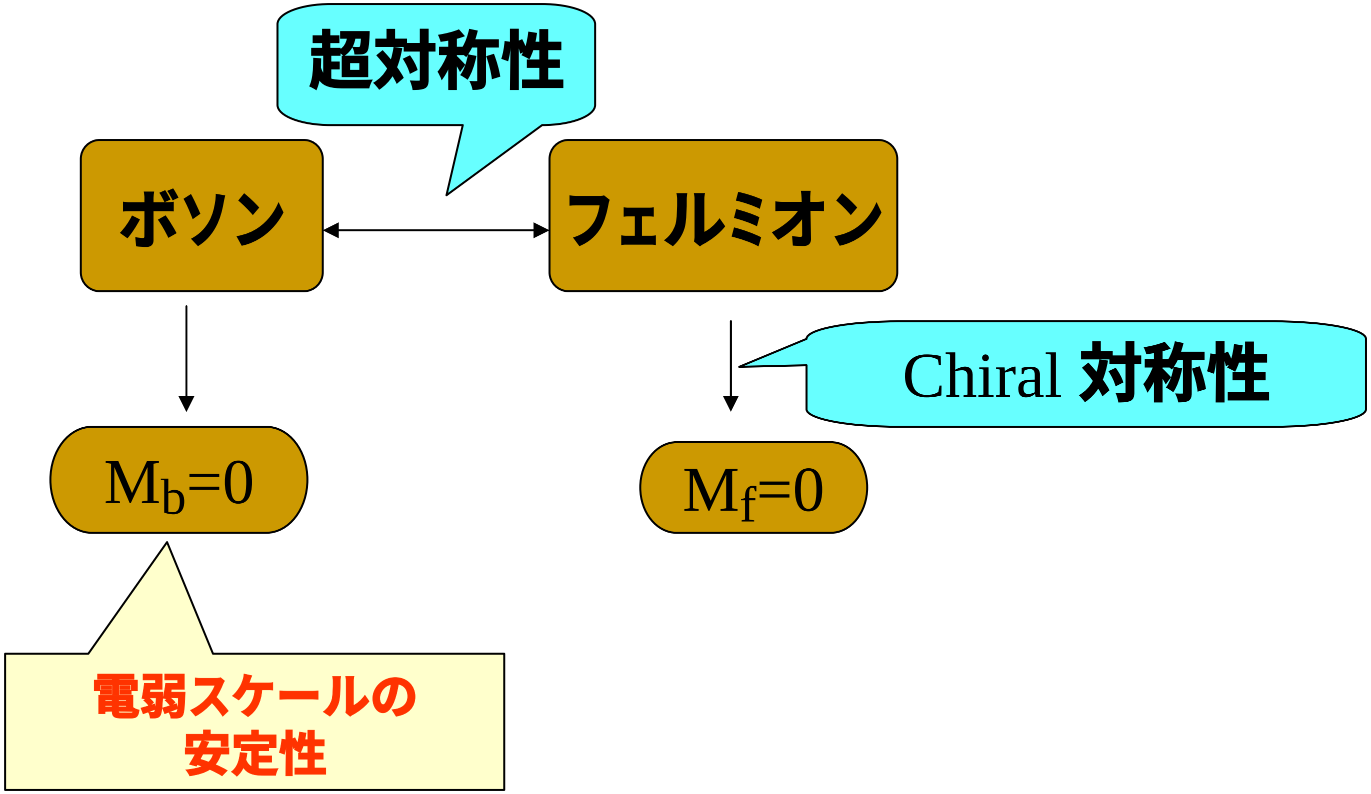


Bare parameter**の**Fine tunining**が必要**→ **不自然！**

- **スカラーの質量をゼロにするような対称性はない**

Cf.　**ベクトル粒子**　**ゲージ対称性**
スピノール　chiral **対称性**

超対称性 (supersymmetry)



超対称性の破れ

- **超対称性が**exact**だと**
  - **ボソンとフェルミオンの質量が縮退**
  - **ところが、**superpartner**は見つかっていない**

  ⇒ **超対称性は破れている**

- Superpartner**が超対称性の破れによって質量をもらっている**

  squark, slepton masses

  gaugino masses

Sfermion Masses (sfermions=squarks & sleptons)

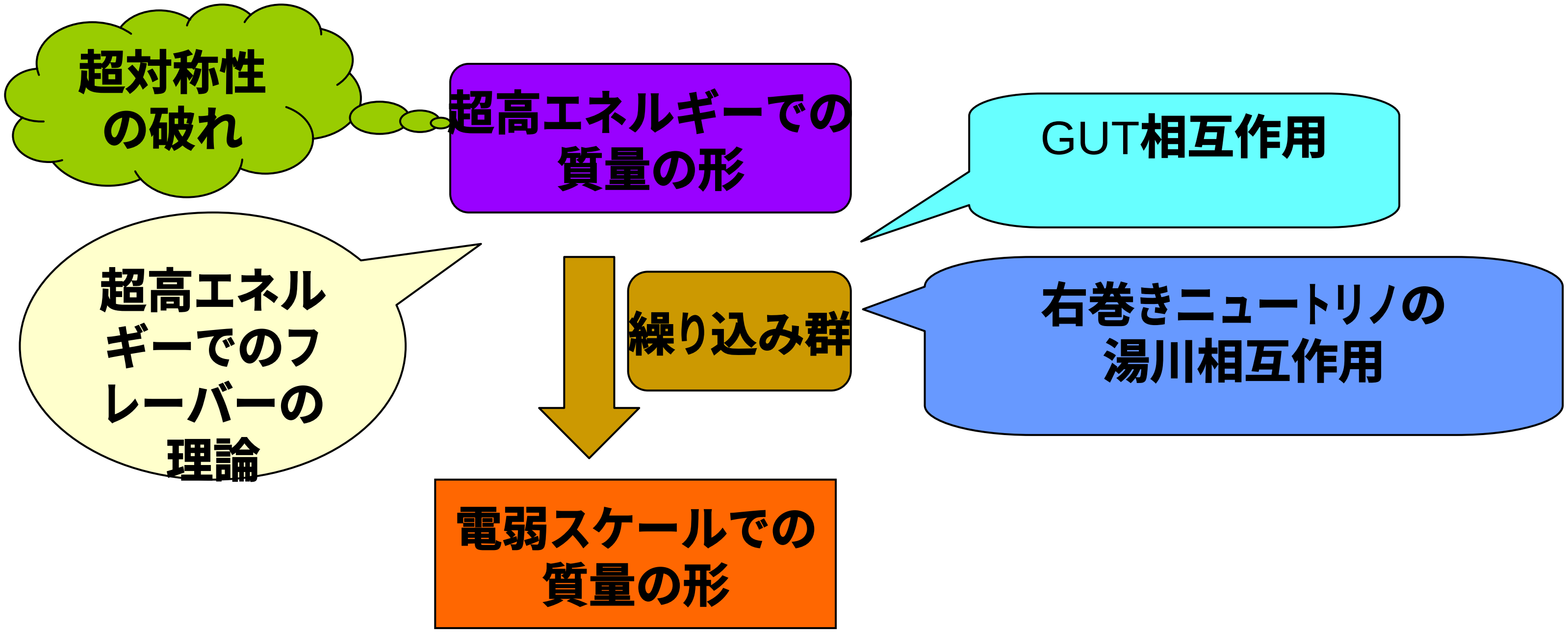
- フェルミオンの質量と違う構造
  - 例) $m^2_{ij}\tilde{q}_i^*\tilde{q}_j$
  - 新しいパラメータ ～100

    [cf. Standard Model 19

    (そのうちフェルミオンの質量と混合 13)]
  - 新しいフレーバー混合の種

超対称性を破るスカラー質量の形

- あらゆるエネルギースケールにおけるフレーバーの情報を含みうる宝の山



Probe to Theory of Flavor

- Interesting Processes
  - **クォークセクター**

    $K-\overline{K}$ $D-\overline{D}$ $B-\overline{B}$

    K rare decays

    $b \to s\,\gamma$

    $B_d \to \phi\, K_s$ etc.
  - **レプトンセクター** (lepton flavor violation, LFV)

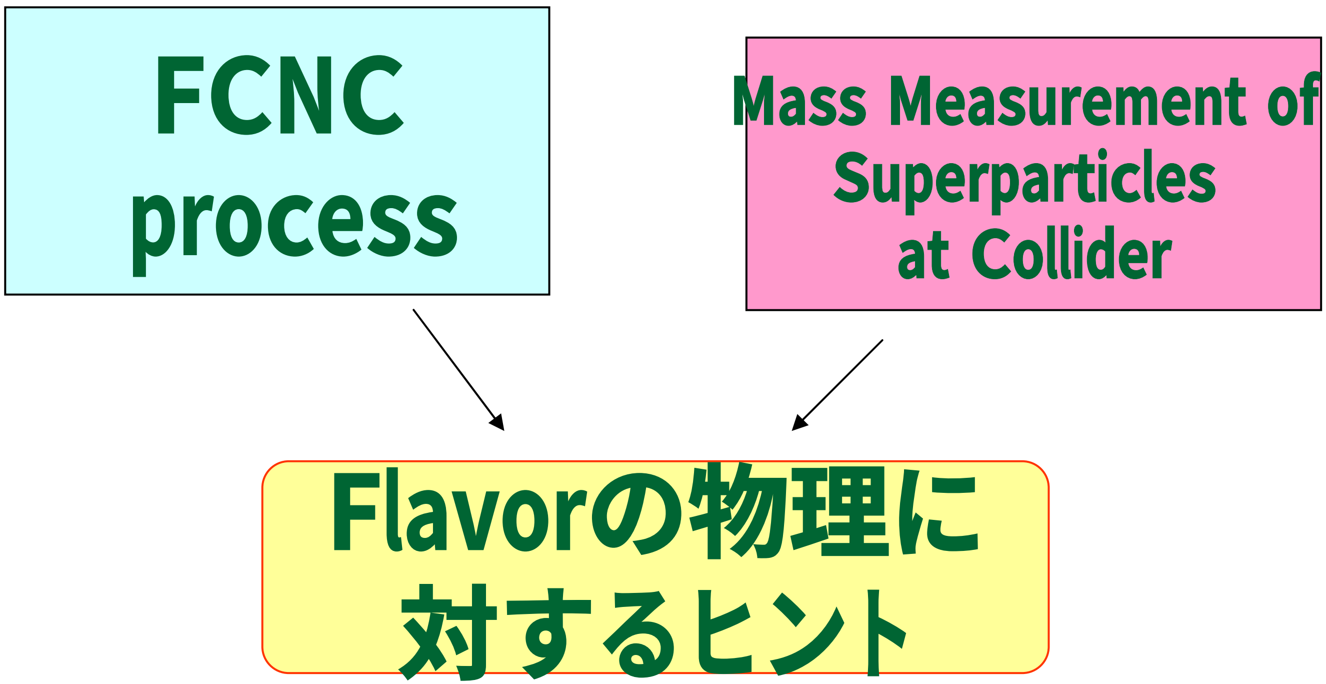
    $\mu \to e\,\gamma$, μ-e conversion, $\tau \to \mu\,\gamma$ etc.
- **以下では、** lepton flavor violation**について議論する。**

SUSY Flavor Problem

- Generic sfermion mass parameters would give too large FCNC!

  $\Leftarrow$ **GIM suppressionされない**
- SUSY**が正しいとすると、何らかの機構によってスフェルミオンのフレーバー混合が抑えられているはずである。**$\rightarrow$ **新しい物理のヒント？？**

$$\Delta m^2_{\tilde{f}\,12} \Big/ m^2_{\tilde{f}} \ll 1$$


FCNC process
Mass Measurement of Superparticles at Collider
Flavorの物理に対するヒント

いくつかのシナリオ

1) Universal Sfermion Masses: e.g. Minimal supergravity

- 最もよく調べられているシナリオ　Good Bench Mark！
- Universalityの正当化？

2) Aligned Sfermion Masses:

- Fermionのflavor mixingとSfermionのflavor mixingが（ほぼ）そろうするシナリオ。FermionとSfermionの質量行列の構造を同時に説明する必要あり。
- 興味深い可能性！　でも、モデルは？

3) その他のシナリオ

mSUGRAの例
NR Yukawaの寄与

Ellis,Hisano,Raidal,Shimizu‘02

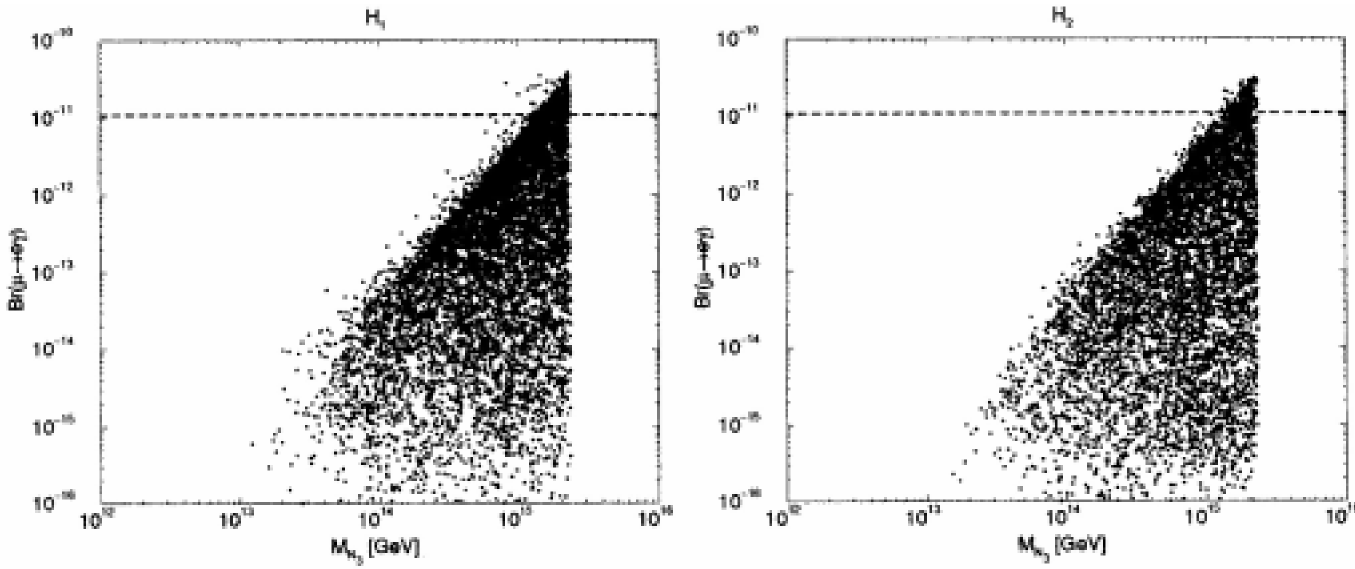


Figure 1: *Scatter plot of* $Br(\mu \to e\gamma)$ *against the heaviest singlet neutrino mass* M_{N_3} *for the ansatz (a)* H_1 *and (b)* H_2. *We take* $m_{1/2} = 300$ *GeV*, $m_0 = 100$ *GeV*, $A_0 = -300$ *GeV*, $\tan\beta = 10$ *and* $sign(\mu) = +1$. *Other input parameters are specified in the text.*

このトークのPart 2では、

- Alignment scenarioにおけるスフェルミオンのフレーバー (特にレプトンセクター) について議論したい。
- スフェルミオンの質量はUVの物理に非常によっている⇒ モデルが必要
- 目的
  - 新しいalignment mechanismを提案する。⇒ Democratic sfermion masses
  - mSUGRA アプローチと比べてどのように予言が変わり得るかを例示する

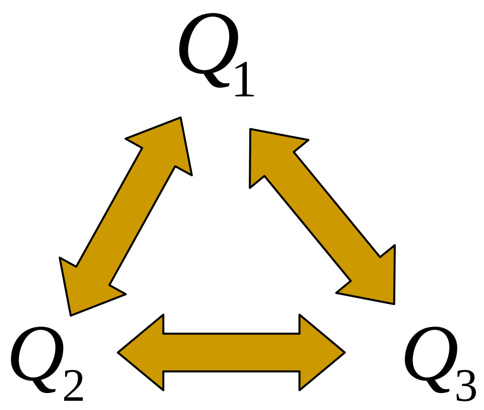
Part 2. Democratic Approach

Democracy to Fermions

- Basic Idea of Democratic (S)fermions:

  3 generations are equal

  → interchangeable



Permutation symmmetry S_3

Q_i are 3 dimensional reprsentation of S_3

- 3 dim. repr. is not an irreducible repr.
- 3 = 1 + 2

$$t \approx \frac{1}{\sqrt{3}}(Q_1 + Q_2 + Q_3)$$

$$c \approx \frac{1}{\sqrt{6}}(Q_1 + Q_2 - 2Q_3)$$

$$u \approx \frac{1}{\sqrt{2}}(Q_1 - Q_2)$$

identified with 3rd generation

Up type quark mass matrix

$S_3(Q_L) \times S_3(U_R)$ sym. Koide

$$m_U \propto \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + \begin{pmatrix} -\varepsilon & 0 & 0 \\ 0 & \varepsilon & 0 \\ 0 & 0 & \delta \end{pmatrix}$$

symmetry breaking term

Quark mass hierarchy $m_t \gg m_c \gg m_u$

Similar Structure for Down-type quarks and Charged leptons

hierarchical masses/ small mixing angles in q sector

Neutrino masses

Fritzch&Xing '96

Fukugita, Tanimoto& Yanagida '98

- We assume that neutrino masses are of Majorana type.
- Only $S_3(L)$ is involved in mass matrix
- There are two $S_3(L)$ invariants

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \qquad m_{\nu ij}\nu_i\nu_j \leftarrow \frac{m_{\nu ij}}{V^2} HHL_iL_j$$

Universal　　　　Democratic

- Unlike the quark case, we take the universal form ← may be justified in extra dimsional scenario (Watari and Yanagida)

$$m_\nu \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} -\varepsilon_\nu & 0 & 0 \\ 0 & \varepsilon_\nu & 0 \\ 0 & 0 & \delta_\nu \end{pmatrix}$$

⇨ Degenerate neutrino mass spectrum

Bi-Large mixing angles for solar and atmospheric neutrinos

Small U_{e3}

Democracy to Sfermion Sector

Hamaguchi,Kakizaki&MY '02

- The democratic ansatz is very successful in fermion masses and mixing.
- They are dictated by S_3symmetries.
- Breaking of the S_3 symmetries may be attributed to the nature of Higgs sector.

- We shall apply the idea of democracy to the sfermion masses.

⇒ Alternative to universal sfermion masses.

Sfermion Masses

Hamaguchi, Kakizaki MY

$$m^2{}_{ij}\tilde{l}_i^*\tilde{l}_j \quad \Leftarrow$$

Non-trivial coupling between visible and hidden sectors in Kaehler potential

Structure: Only one S_3 is involved.

There are two S_3 invariants

$$m_{ij}^2 = m_0^2 \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \rho \frac{1}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \right]$$

universal democratic

- Diagonalization

$$m_{ij}^2 \Rightarrow m_0^2 \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1+\rho \end{pmatrix}$$

- If $\rho \neq 0$, then the sfermion masses are characterized by
  - non-degeneracy

    $$m_{1st} = m_{2nd} \neq m_{3rd}$$

  - flavor mixing

    $$U_f^\dagger m_0^2 \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1+\rho \end{pmatrix} U_f$$:no longer diagonal

U_f is almost unit matrix. Deviation from the unit matrix comes from the S_3 breaking.

Flavor mixing of sfermion masses is small, though the masses are not degenerate. ⇐ alignment mechanism

Left-handed Slepton Masses

$$\frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

- Democratic part in Kaehler potential for left-handed lepton doublets

⇨ Non-canonical kinetic terms

⇨ effectively induces democratic part in neutrino mass

- It would upset the successful pattern of neutrino mass matrix
- Thus the democratic part should be absent in Kaehler potential $\therefore \rho = 0$
- Universal mass for left-handed sleptons

Slepton Masses and LFV

In our model with democratic ansatz

- Right-handed sleptons $\tilde{l}_{Ri}$ $\rho \neq 0$

  non-degenerate masses

  flavor mixing

- Left-handed sleptons $\tilde{l}_{Li}$ $\rho = 0$

  degenerate (and universal) masses

  no flavor mixing

Unique Predictions

- Collider Physics

$$m_{\tilde{e}R} = m_{\tilde{\mu}R} \neq m_{\tilde{\tau}R} \qquad m_{\tilde{e}L} = m_{\tilde{\mu}L} = m_{\tilde{\tau}L}$$

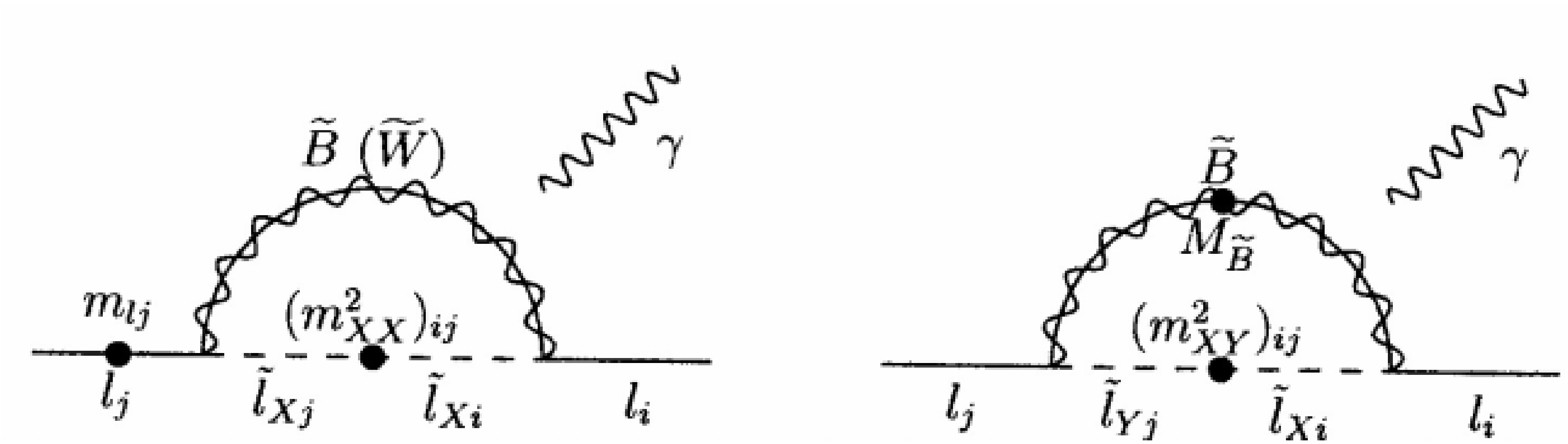
This is testable in future collider experiments!

- Lepton Flavor Violation (LFV)

$\mu \rightarrow e\, \gamma$ arises from right-handed slepton exchanges.

Typical Feynman Diagrams

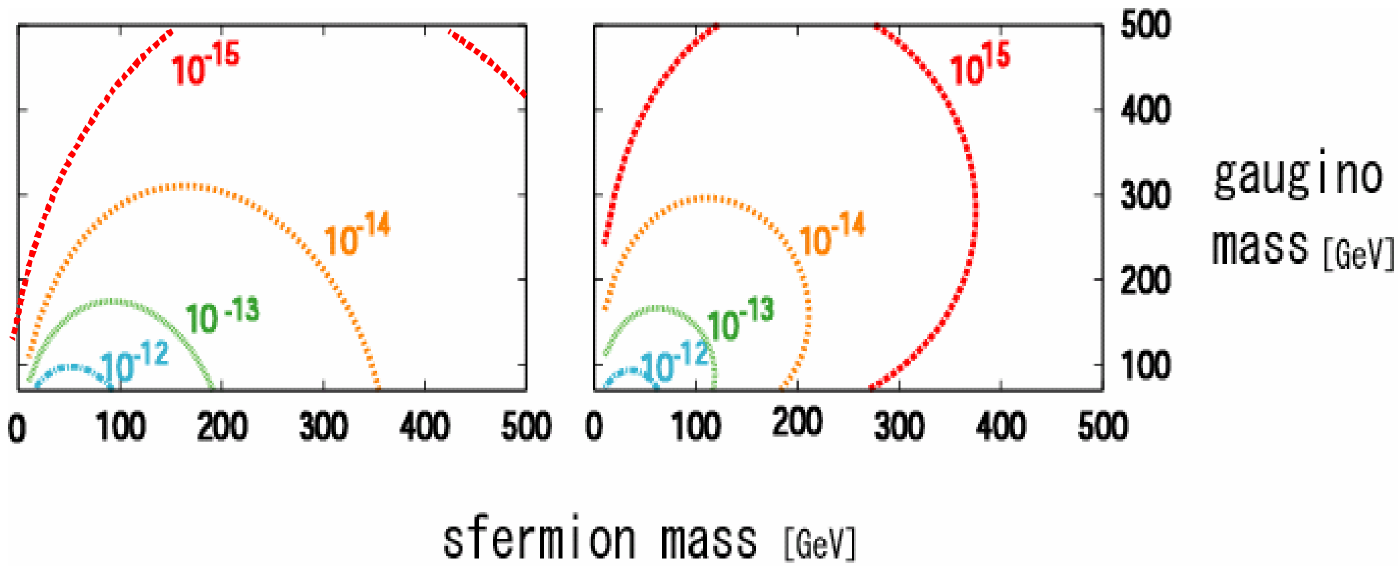
$$\mu \rightarrow e\gamma$$



Branching Ratio Br ($\mu \to e\,\gamma$)

- Current Exp. Bound Br($\mu \to e\,\gamma$)<1.2 $\times 10^{-11}$
- Future Reach (MeG) $\sim 10^{-14}$
- In our model, $\mu \to e\,\gamma$ will be observed as far as the sparticle masses are close to electroweak scale.

ρ=1, a=0 ρ=0.1, a=m



Comparison

Minimal SUGRA $\oplus$ RG from NR Yukawa	Democratic Approach
Left-handed stau is lighter than others.	Right-handed stau is either lighter or heavier than others
Left-handed sleptons have LFV	Right-handed sleptons have LFV.
$\Rightarrow$ $\mu_R^- \to e_L^- + \gamma$	$\Rightarrow$ $\mu_L^- \to e_R^- + \gamma$

testable in collider exp

Polarized muon may be important to distinguish each other.

まとめ

- SUSY SM has more than 100 parameters for sfermion masses and mixing. Generic parameters would predict too large FCNC.
- We propose a democratic approach to fermion and sfermion masses as a solution to the SUSY FCNC problem.
- This model has unique predictions on slepton masses and LFV ($\mu \to e\,\gamma$, μ-e conversion), which will be testable in future experiments.
- A more general conclusion is that collider experiments and LFV processes (and other FCNC processes in hadron sector) will provide crucial hints to distinguish the theory of flavor.