Lepton Flavor Violations from soft SUSY breaking terms in modular flavor models

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based on

"Soft supersymmetry breaking terms and lepton flavor violations in modular flavor model"

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in collaboration with

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Introduction

- The origin of flavor is one of the important questions in particle physics.
  - Non-Abelian flavor symmetries are interesting approach,

S_3, A_4, S_4, A_5, etc

A_4 is minimal to embed three families of leptons in one irreducible rep. [E. Ma and G. Rajasekarn, PRD (2001)]

- Modular symmetry is a new direction of flavor symmetry approach. [Ferugulio, 1706.08749]
  - Modular symmetry arises from the compatification of higher dimensions in superstring theory.
  - Modular groups Γ_N are isomorphic to the finite groups,

$$\boldsymbol{\Gamma_2 \simeq S_3,\ \Gamma_3 \simeq A_4,\ \Gamma_4 \simeq S_4,\ \Gamma_5 \simeq A_5,}$$

[Kobayashi et al, PRD (2018)]
[Tanedo, Petcov, NPB (2019)]
[Novichkov et al, JHEP (2019)]

  - The modulus $\boldsymbol{\tau}$ which characterizes the shape of compact space plays an important role to determine flavor structure.
  - The lepton mass matrix can be given by the modular forms.

(Flavons are not necessary in modular symmetry models)

Introduction

- Flavor symmetries also control flavor structure of superpartners.
  [Ko, et al PRD (2008), Ishimori et al PRD (2008), etc]
  - Specific patterns appears in soft SUSY breaking terms.
  - Such specific patterns can be observed in LFV processes like $\mu \to e+\gamma$ if SUSY particles are light. [See e.g. Kobayashi and Vives, PLB (2001)]
- In modular symmetry models, the *F*-term of the modulus τ can be non-vanishing, and lead to SUSY breaking.
  - Such SUSY breaking terms show specific patterns of modular symm.

In this talk,

- Flavour structure of soft SUSY breaking terms from the modulus *F*-term in simple modular A_4 models.
- $\mu \to e+\gamma$ decay to see flavor structure and parameter dependence.

Modular Symmetry

[Feruglio, 1706.08749]

- Modular transformations γ acting on the modulus τ

$$\tau \longrightarrow \gamma\tau = \frac{a\tau + b}{c\tau + d} \quad \text{where } a, b, c, d \in \mathbb{Z} \text{ and } ad - bc = 1, \quad \mathrm{Im}[\tau] > 0$$

- Chiral superfield with modular weight $-k_I$ transforms as

$$\phi^{(I)} \to (c\tau + d)^{-k_I} \rho^{(I)}(\gamma) \phi^{(I)}, \qquad \rho^{(I)}(\gamma)$$

: unitary rep. matrix

- Holomorphic functions which transform under modular trans., are called modular form with weight k

$$f(\tau) \to (c\tau + d)^k f(\tau),$$

- Superpotential can be formed using chiral superfields and modular forms

$$\mathcal{W} = f(\tau)\phi^{(I_1)}\phi^{(I_2)}\cdots\phi^{(I_n)},$$

The superpotential is invariant under the modular trans. when

$$\rho^{(I_1)} \times \rho^{(I_2)} \cdots \times \rho^{(I_n)} = 1$$

$$k - k_{I_1} - k_{I_2} \cdots - k_{I_n} = 0$$

[Okada and Tanimoto, EPJC(2021), PRD(2021), JHEP(2021)]
[Kobayshi et al, JHEP(2018), Asaka et al, JHEP(2019)]

Modular A_4 flavor model

- We consider two models in which the charged lepton Yukawa is given by A_4 triplet modular form with weight 2.

Model A : Weinberg operator

	L	(e^c, μ^c, τ^c)	$H_{u,d}$	$Y_{\mathbf{r}}^{(2)}, \quad Y_{\mathbf{r}}^{(4)}$
$SU(2)$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
A_4	$\mathbf{3}$	$(\mathbf{1}, \mathbf{1}'', \mathbf{1}')$	$\mathbf{1}$	$\mathbf{3}, \{\mathbf{3}, \mathbf{1}, \mathbf{1}'\}$
k	-2	0	0	$2, \quad 4$

Neutrino superpotential

$$W_\nu = -\frac{1}{\Lambda}(H_u H_u L L Y_r^{(4)})_1$$

Model B : type-I Seesaw

L	(e^c, μ^c, τ^c)	ν^c	$H_{u,d}$	$Y_{\mathbf{3}}^{(2)}$
$\mathbf{2}$ $\mathbf{3}$ -1	$\mathbf{1}$ $(\mathbf{1}, \mathbf{1}'', \mathbf{1}')$ -1	$\mathbf{1}$ $\mathbf{3}$ -1	$\mathbf{2}$ $\mathbf{1}$ 0	$\mathbf{1}$ $\mathbf{3}$ 2

Neutrino superpotential

$$W_\nu = g(L Y_3^{(2)} \nu^c)_1 H_u + \Lambda(Y_3^{(2)} \nu^c \nu^c)_1$$

Charged lepton superpotential

$$W_e = \alpha(L Y_3^{(2)})_1 e_R^c H_d + \beta(L Y_3^{(2)})_{1'} \mu_R^c H_d + \gamma(L Y_3^{(2)})_{1''} \tau_R^c H_d$$

$\alpha, \ \beta, \ \gamma$: fixed by charged lepton masses

Charged Lepton Yukawa

- The triplet modular form with weight 2

$$Y_3^{(2)} = \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \end{pmatrix} \quad \text{satisfying} \quad Y_2^2 + 2Y_1Y_3 = 0$$

- Charged lepton Yukawa

$$W_e = \alpha(LY_3^{(2)})_1 e_R^c H_d + \beta(LY_3^{(2)})_{1'} \mu_R^c H_d + \gamma(LY_3^{(2)})_{1''} \tau_R^c H_d$$

$$\supset l_{Ri} Y_{ijk} H_j l_{Lk}$$

$$\rightarrow \quad Y_{ijk} = \mathrm{diag}[\alpha, \beta, \gamma] \begin{pmatrix} Y_1 & Y_3 & Y_2 \\ Y_2 & Y_1 & Y_3 \\ Y_3 & Y_2 & Y_1 \end{pmatrix}_{RL}, \quad (i,k = e,\mu,\tau,\ j = H_d)$$

- Y_i (i=1,2,3) is a function of the modulus τ.

$$Y_3^{(2)} = \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \end{pmatrix} = \begin{pmatrix} 1 + 12q + 36q^2 + 12q^3 + \cdots \\ -6q^{1/3}(1 + 7q + 8q^2 + \cdots) \\ -18q^{2/3}(1 + 2q + 5q^2 + \cdots) \end{pmatrix} \quad \text{with} \quad q = e^{2\pi i \tau}$$

Once τ is determined, the Yukawa is fixed.

Soft SUSY breaking terms

[SUSY breaking: Kaplunovsky and Louis, PLB306, 1993]

[Kobayashi, TS, Tanimoto, arxiv:2102.10425]

- Soft SUSY breaking terms originating from the modulus *F*-term are given in supergravity theory. (M_p=1)

$$\mathcal{L}_{\rm soft} = \tilde{m}_L^2 \tilde{L}^\dagger \tilde{L} + \tilde{m}_e^2 \tilde{e}_R^\dagger \tilde{e}_R + (\underline{Y}\, A \tilde{L}^\dagger H \tilde{e_R} + h.c.)$$

charged lepton Yukawa

soft mass

$$\tilde{m}_i^2 = m_{3/2}^2 - k_i \frac{|F^\tau|^2}{(2\mathrm{Im}(\tau))} = m_0^2$$

k_i is common for 3 flavor.

flavor universal

A-term

$$A_{ijk} = A^0_{ijk} + A'_{ijk}$$

where

$$A^0_{ijk} = (1 - k_i - k_j - k_k)\frac{F^\tau}{(2\mathrm{Im}(\tau))} = A^0$$

flavor universal

$$A'_{ijk} = \frac{F^\tau}{Y_{ijk}} \frac{dY_{ijk}(\tau)}{d\tau}$$

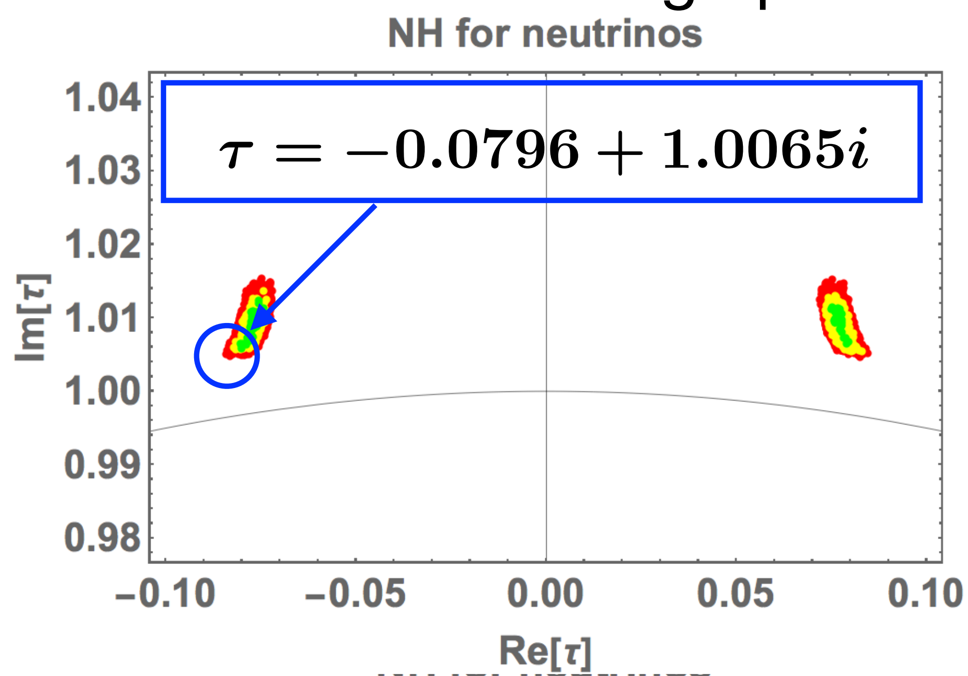
flavor dependent

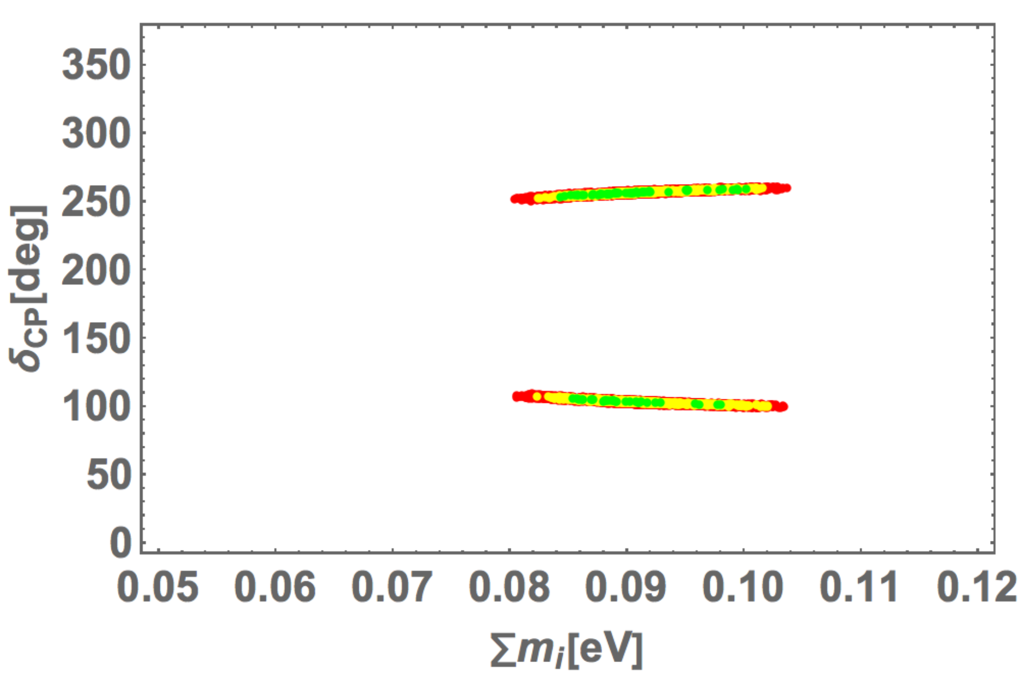
Modular form (*Y*) determines the flavor structure of *A* term

Allowed region of Modulus

- Neutrino Yukawa is also given by modular forms.
- The modulus is determined by neutrino oscillation data in each model

Model A : Weinberg operator

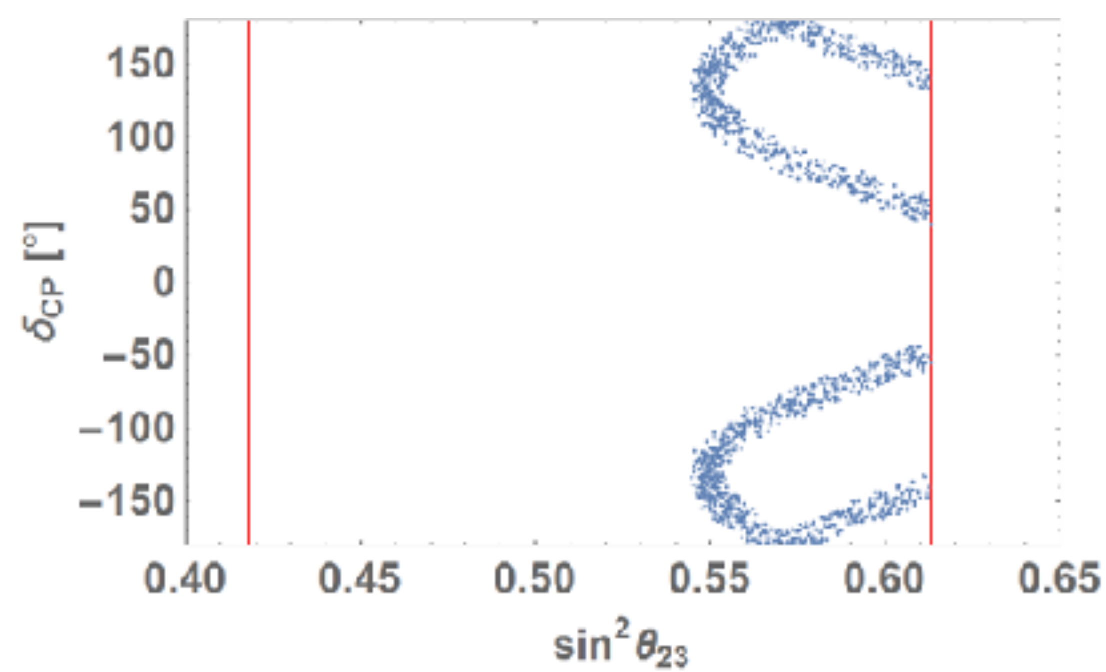




Model B : type-I Seesaw

Im[τ]	Re[τ]
$0.66-0.73$	$\pm(0.25-0.31)$, $\pm(0.46-0.54)$,
$1.17-1.32$	$\pm(0.66-0.75)$, $\pm(1.25-1.31)$, $\pm(1.46-1.50)$

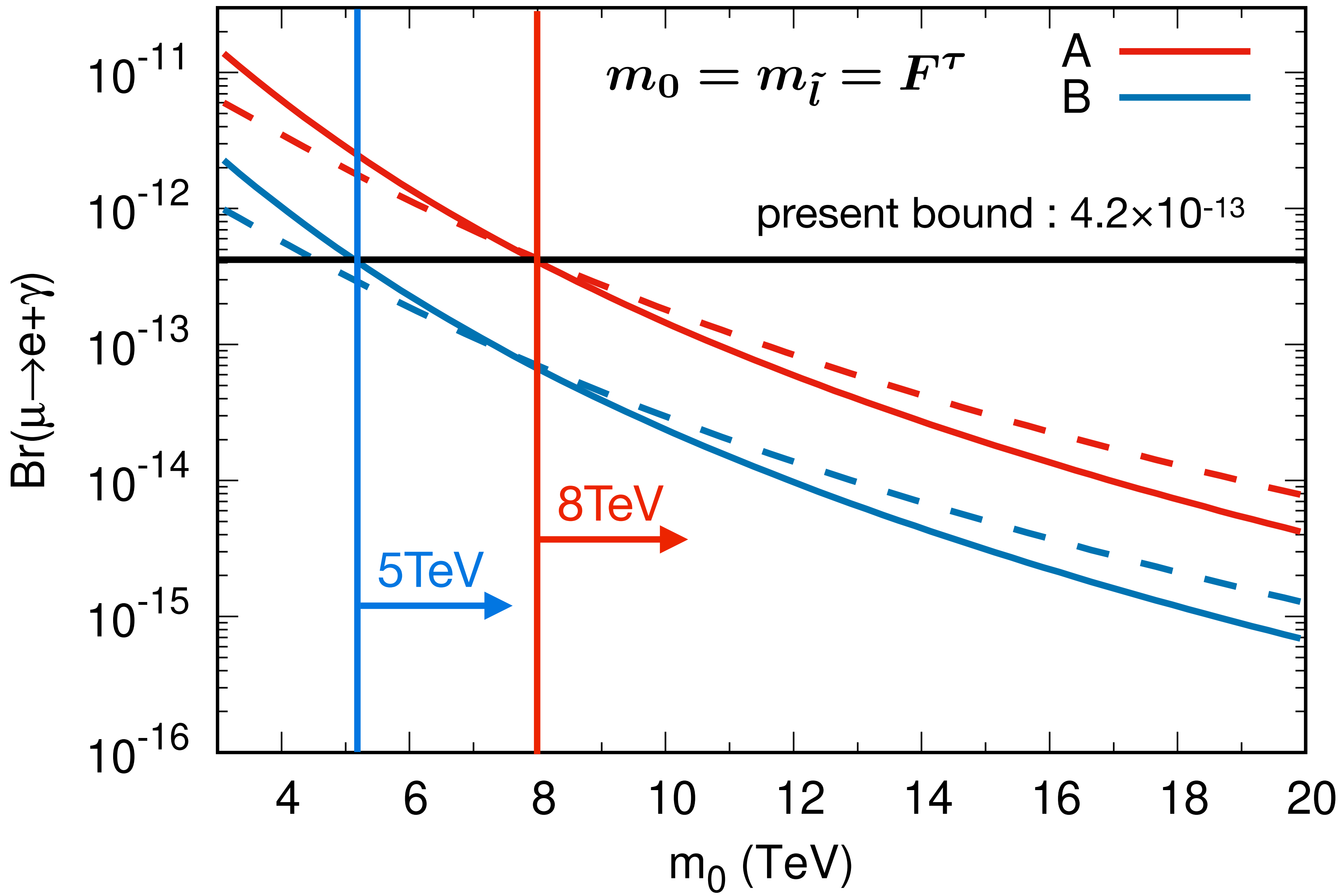
$$\tau = 0.48151 + 1.30262i$$



SUSY mass scale dependence

A: $\tau = -0.0796 + 1.0065i$
$\alpha/\gamma = 6.82 \times 10^{-2}, \ \ \beta/\gamma = 1.02 \times 10^{-3}$

B: $\tau = 0.48151 + 1.30262i$
$\alpha/\gamma = 2.03 \times 10^{2}, \ \ \beta/\gamma = 3.30 \times 10^{3}$



gaugino mass

solid:
$M_1 = 3$ TeV

dashed:
$M_1 = 5$ TeV

with $\tan\beta = 5$

Mass insertions

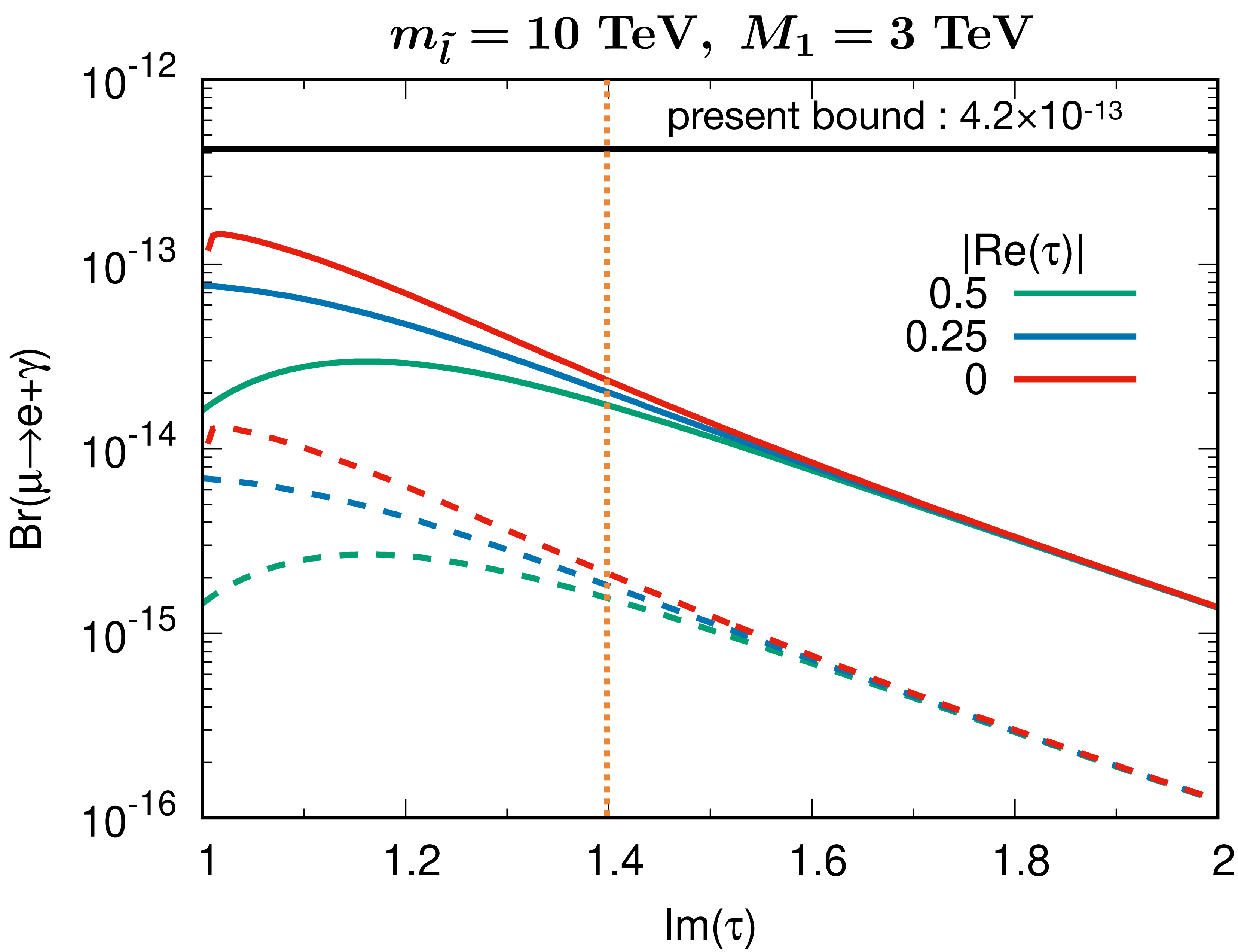
A: $|(\delta_\ell^{RL})_{\mu e}| \simeq 2.1 \times 10^{-5} \left(\frac{F^\tau}{10\ \mathrm{TeV}}\right)$

$|(\delta_\ell^{LR})_{\mu e}| \simeq 9.7 \times 10^{-8} \left(\frac{F^\tau}{10\ \mathrm{TeV}}\right)$

B: $|(\delta_\ell^{RL})_{\mu e}| \simeq 8.4 \times 10^{-6} \left(\frac{F^\tau}{10\ \mathrm{TeV}}\right)$

$|(\delta_\ell^{LR})_{\mu e}| \simeq 3.7 \times 10^{-8} \left(\frac{F^\tau}{10\ \mathrm{TeV}}\right)$

Modulus dependence



solid: $F^\tau = m_{\tilde{l}}$

dashed: $F^\tau = M_1$

Depends on both Re(τ) and Im(τ) below Im(τ) < 1.4

Summary

We have studied the SUSY breaking and LFV in modular flavor models,

- Soft SUSY breaking terms from the modulus F-term are obtained.
- Flavor structure of the SUSY breaking terms are determined by modular form of the charged leptons.

and showed the LFV decay in two A_4 models,

- The SUSY mass scales are larger than 8 (model A) and 5 (B) TeV.
- The branching ratio significantly depends on τ for $\mathrm{Im}(\tau) < 1.4$, and is independent of $\mathrm{Re}(\tau)$ for larger $\mathrm{Im}(\tau)$.

Messages are

- Similar and detailed analyses are important in other flavor models.
- Specific patterns of soft SUSY br. terms are studied in LFV process.