How can CP phases contribute to LFV processes ?

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Why LFV ?

- LHC is one of the most promising way to find new physics.
- Typical (or lower limit fow) mass scale of the new physics will be obtained at the begining stage of LHC.
  - If SUSY is realized below TeV scale, masses of SUSY particles will be measured.
- Significant flavour signals are naturally expected in BSM at TeV scale.
- Charged lepton flavour violation is strongly suppressed in the standard model.

  $\Rightarrow$ LFV = evidence of new physics
- MSSM+Seesaw mechanism (even in the case of flavour universal SUSY breakings) $\Rightarrow$ Large LFV
  - Low energy neutrino parameters (mass, mixing, CP-phases) can be related to prediction of LFV.
  - There are additional d.o.f. in neutrino Yukawa sector...

Importance of CP phases

- CP is violated in nature.
  - Baryogenesis require CP phase.
  - CKM phase is measured.
- Neutrino Yukawa couplings should have CP phases, though CPV in lepton sector is not obserbed...
  - Leptogenesis require CP phases.
  - In SUSY GUT, these CP phases contribute to hadronic EDM.

Question

How they contribute to LFV predictions ?

Seesaw model

Seesaw model (Type I) is a very attractive model to explain the smallness of neutrino masses.

- Introducing right-handed neutrinos to the SM
- ν_R is SM singlet $\Rightarrow$ Majorana mass terms
- If Majorana mass is heavy $\rightarrow$ we can obtain light neutrinos

$$-\mathcal{L} = Y_E \bar{e}_R l_L h_d + Y_N \bar{\nu}_R l_L \cdot h_u + \frac{1}{2} M_R \bar{\nu}_R \nu_R^c$$

$\Downarrow$: RN are integlated out

$$-\mathcal{L} = Y_E \bar{e}_R l_L \cdot h_D - \frac{1}{2}\kappa (l_L \cdot h_u)^2 \ , \quad \kappa = Y_N^T M_R^{-1} Y_N$$

The neutrino mass matrix is:

$$m_\nu = \frac{\langle h_u \rangle^2}{2}\kappa = \frac{\langle h_u \rangle^2}{2} Y_N^T \frac{1}{M_R} Y_N$$

Parametrization

Solving the seesaw relation, $\frac{\langle h_u \rangle^2}{2} Y_N^T M_R^{-1} Y_N = m_\nu$, Y_N can be parametrized as

$$\frac{\langle h_u \rangle}{\sqrt{2}} Y_N = \sqrt{D_M} \mathbf{R} \sqrt{D_m} U^\dagger$$

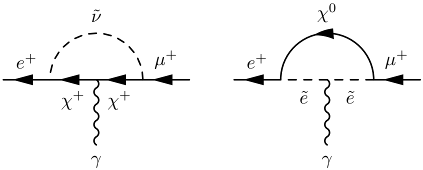
J.A. Casas, A. Ibarra, NPB618,171

$D_M = \mathrm{diag}(M_1, M_2, M_3)$: RN masses
$D_m = \mathrm{diag}(m_1, m_2, m_3)$, $\Delta m_\odot^2 \equiv m_2^2 - m_1^2$, $|\Delta m_A^2| = |m_3^2 - m_1^2|$
$U = U_{\mathrm{osc}} P_M$, $P_M = \mathrm{diag}(1, e^{-i\alpha/2}, e^{-i\beta/2})$: PMNS matrix
R is a complex orthogonal matrix, $\mathbf{R}^T \mathbf{R} = \mathbf{1}$

- $|U_{13}| = s_{13}$ and CP phases are not determined yet.
  - There is an upper bound on s_{13}, $s_{13} \leq 0.2$.
- **R** has 6 real parameters
- D_M and **R**: High energy parameters
  D_m and U: low energy parameters
- Without considering flavour effect, thermal leptogenesis requires a complex **R**.

SUSY and LFV

In MSSM+RN, slepton exchange diagrams contribute to LFV processes



$$\mathrm{B}(l_i \to l_j\gamma) \simeq \frac{\alpha^3}{G_F^2}\frac{\left|(\tilde{M}_L^2)_{ij}\right|^2}{m_S^8}\frac{\langle h_d\rangle^2}{\langle h_u\rangle^2} \propto |(y_N^\dagger L y_N)_{ij}|^2$$

$$L = \mathrm{diag}(\ln\frac{M_1}{M_X}, \ln\frac{M_2}{M_X}, \ln\frac{M_3}{M_X})$$

F. Borzumati, A. Masiero, PRL57,961;
J.Hisano, T. Moroi, K. Tobe, M. Yamaguchi, T. Yanagida, PLB357, 579;
J.A. Casas, A. Ibarra, NPB618,171...

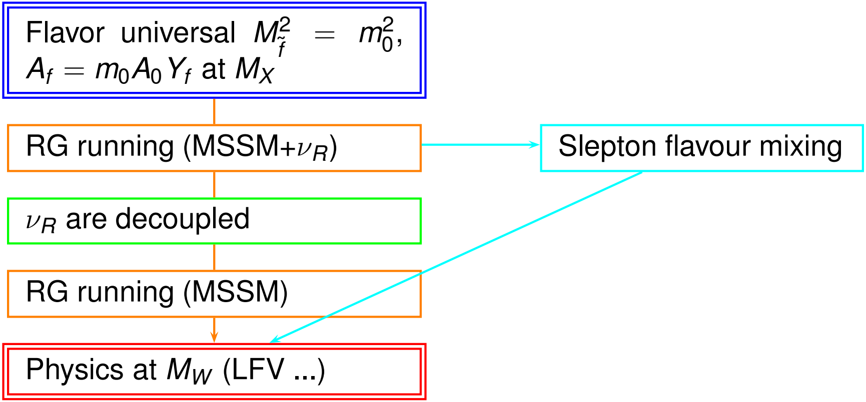
$$m_S^8 \simeq 0.5 m_0^2 M_{1/2}^2 (m_0^2 + 0.6 M_{1/2}^2)^2$$

S.T. Petcov, S. Profumo, Y. Takanishi, C.E. Yaguna, NPB676, 453

How they come

Assumption

- SUSY breaking terms are flavor universal at $M_X (M_G$ or $M_P)$



Quasi-degenerate heavy neutrinos

S. T. Petcov and T.S., hep-ph/0605151

A most simple case is quasi-degenerate heavy neutrino case:
$M_1 \simeq M_2 \simeq M_3$
In the limit of $M_1 = M_2 = M_3$, 3 d.o.f. in $\mathbf{R}$ can be rotated out
$\frac{\langle h_u \rangle}{\sqrt{2}} Y_N = \sqrt{D_M}\mathbf{R}\sqrt{D_m}U^\dagger = \sqrt{D_M}\mathbf{O}\mathbf{R}\sqrt{D_m}U^\dagger \equiv \sqrt{D_M}\mathbf{R}'\sqrt{D_m}U^\dagger$

Then, we can parametrise

$$\mathbf{R} = e^{i\mathbf{A}} \;, \quad \mathbf{A} = \begin{pmatrix} 0 & a & b \\ -a & 0 & c \\ -b & -c & 0 \end{pmatrix}$$

For light neutrino spectrum, we will consider three typical cases

- Normal Hierarchical case: $m_1 \simeq 0$, $m_1 \ll m_2 \ll m_3$
- Inverted Hierarchical case: $m_3 \simeq 0$, $m_3 \ll m_1 \sim m_2$

We consider the ratio of the branching ratios, *e.g.*,

$$\frac{\mathrm{Br}(\mu \to e\gamma)}{\mathrm{Br}(\tau \to \mu\gamma)} \propto \frac{|(Y_N^\dagger Y_N)_{21}|^2}{|(Y_N^\dagger Y_N)_{32}|^2} \equiv R(21/32), \text{ etc}$$

NH-ν_L case

In the limit of $m_1 = 0$,

$$(Y_N^\dagger Y_N)_{12} = \Delta_{21} c_{23} c_{12} s_{12} + \Delta_{31} s_{23} s_{13} e^{-i\delta}$$

$$+ 2\frac{M_R}{v_u^2} i c \sqrt{m_2 m_3} \left(s_{23} s_{12} e^{i\frac{\alpha-\beta_M}{2}} - c_{23} s_{13} c_{12} e^{-i(\frac{\alpha-\beta_M}{2}+\delta)} \right) + \cdots$$

$$(Y_N^\dagger Y_N)_{13} = -\Delta_{21} s_{23} c_{12} s_{12} + \Delta_{31} c_{23} s_{13} e^{-i\delta}$$

$$+ 2\frac{M_R}{v_u^2} i c \sqrt{m_2 m_3} \left(s_{12} c_{23} e^{i\frac{\alpha-\beta_M}{2}} + s_{13} c_{12} s_{23} e^{-i(\frac{\alpha-\beta_M}{2}+\delta)} \right) + \cdots$$

$$(Y_N^\dagger Y_N)_{23} = \Delta_{31} s_{23} c_{23}$$

$$+ 2\frac{M_R}{v_u^2} i c \sqrt{m_2 m_3} \left(c_{12}(c_{23}^2 e^{i\frac{\alpha-\beta_M}{2}} + s_{23}^2 e^{-i\frac{\alpha-\beta_M}{2}}) + \cdots \right) + \cdots$$

- a- and b- dependence is weaker than c-dependence.
- $(Y_N^\dagger Y_N)_{23}$ depends weakly on the phases.
- The cancelation can happen for specific α, β and δ.

IH-ν_L case

In the limit of $m_3 = 0$,

$$(Y_N^\dagger Y_N)_{12} = \Delta_{21} c_{23} c_{12} s_{12} + \Delta_{31} s_{23} s_{13} e^{-i\delta}$$

$$+ 2\frac{M_R}{v_u^2} i a \sqrt{m_1 m_2} \left(c_{23}(c_{12}^2 e^{-i\frac{\alpha}{2}} + s_{12}^2 e^{i\frac{\alpha}{2}}) + 2i\, s_{13} c_{12} s_{12} s_{23}\ e^{-i\delta} \sin\frac{\alpha}{2} \right) + \cdots$$

$$(Y_N^\dagger Y_N)_{13} = -\Delta_{21} s_{23} c_{12} s_{12} + \Delta_{31} c_{23} s_{13} e^{-i\delta}$$

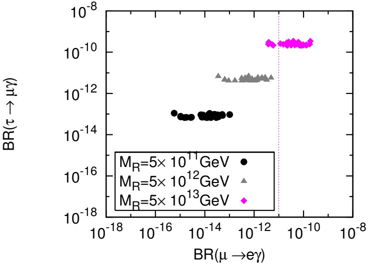
$$- 2\frac{M_R}{v_u^2} i a \sqrt{m_1 m_2} \left(s_{23}(c_{12}^2 e^{-i\frac{\alpha}{2}} + s_{12}^2 e^{i\frac{\alpha}{2}}) - 2i\, s_{13} c_{12} s_{12} c_{23}\ e^{-i\delta} \sin\frac{\alpha}{2} \right) + \cdots$$

$$(Y_N^\dagger Y_N)_{23} = \Delta_{31} s_{23} c_{23}$$

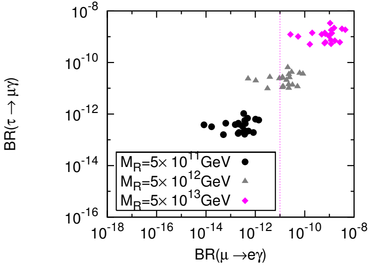
$$+ 2\frac{M_R}{v_u^2} i a \sqrt{m_1 m_2} \left(-2i c_{12} s_{12} c_{23} s_{23} \sin\frac{\alpha}{2} + \cdots \right) + \cdots$$

- They depend on "a"
- $(Y_N^\dagger Y_N)_{23}$ depends weakly on the phases.
- The cancelation can happen for specific α, β and δ.

$\mu \to e\gamma$ and $\tau \to \mu\gamma$



(NH)



(IH)

SUSY parameters are taken as SPS1a;
$\tan\beta = 10$, $m_0 = 100$GeV, $m_{1/2} = 250$GeV, $A_0 = -100$GeV

Br($\tau \to \mu\gamma$) weakly depends on CP phases (both low and high energy phase)

Hierarchical RN case

We move to $M_1 \ll M_2 \ll M_3$ case

S. T. Petcov, W. Rodejohann, T. S and Y. Takanishi,NPB739,208 (2006)

The off-diagonal element relevant to $\mu \to e\gamma$ is

$$
\begin{aligned}
(Y_N^\dagger L Y_N)_{21} = & \frac{M_3}{v_u^2} \ln \frac{M_3}{M_X} (\mathbf{R}\sqrt{D_\nu} U^\dagger)^*_{32} (\mathbf{R}\sqrt{D_\nu} U^\dagger)_{31} \\
& + \frac{M_2}{v_u^2} \ln \frac{M_2}{M_X} (\mathbf{R}\sqrt{D_\nu} U^\dagger)^*_{22} (\mathbf{R}\sqrt{D_\nu} U^\dagger)_{21} \\
& + \frac{M_1}{v_u^2} \ln \frac{M_1}{M_X} (\mathbf{R}\sqrt{D_\nu} U^\dagger)^*_{12} (\mathbf{R}\sqrt{D_\nu} U^\dagger)_{11}
\end{aligned}
$$

One possible way to avoid too large contributions to $\mu \to e\gamma$ is suppressing the M_3 contribution
$\Rightarrow (\mathbf{R}\sqrt{D_\nu} U^\dagger)^*_{32} = 0$ or $(\mathbf{R}\sqrt{D_\nu} U^\dagger)^*_{31} = 0$

Light neutrino spectrum and R

S. T. Petcov, W. Rodejohann, T. S and Y. Takanishi,NPB739,208 (2006)

Natural way to realize the above situation is:

- NH: $m_1 \sim 0$, $m_2 \ll m_3$
  $$\Rightarrow \mathbf{R} = \begin{pmatrix} 0 & \sin\omega & \cos\omega \\ 0 & \cos\omega & \sin\omega \\ -1 & 0 & 0 \end{pmatrix} \to Y_N = \begin{pmatrix} * & * & * \\ * & * & * \\ 0 & 0 & 0 \end{pmatrix}$$
- IH: $m_3 \sim 0$, $m_1 \sim m_2 \sim 0.05\text{eV}$
  $$\Rightarrow \mathbf{R} = \begin{pmatrix} \cos\omega & \sin\omega & 0 \\ -\sin\omega & \cos\omega & 0 \\ 0 & 0 & 1 \end{pmatrix} \to Y_N = \begin{pmatrix} * & * & * \\ * & * & * \\ 0 & 0 & 0 \end{pmatrix}$$
- QD: $m_1 \sim m_2 \sim m_3 \sim \mathcal{O}(0.1)\text{eV}$
  $$\Rightarrow (Y_N^\dagger L Y_N)_{21} \sim \frac{L_3 m M_3}{v_u^2} s_{23} c_{13} s_{13} + \cdots$$
  with the same R as it in IH case

Note: ω is a complex parameter

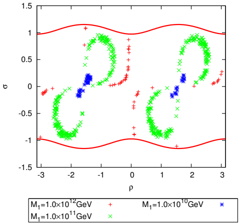
Leptogenesis

S. T. Petcov, W. Rodejohann, T. S and Y. Takanishi,NPB739,208 (2006)

If we consider the thermal leptogenesis scenario, we obtain strong constraint on M_1 and $\omega \equiv \rho + i\sigma$.

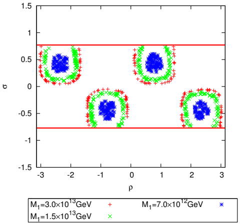
♠The CP asymmetry parameter ϵ can be written by $Y_N Y_N^\dagger$.

$Y_B \sim (6.0 \pm 1.0) \times 10^{-10} \Rightarrow$



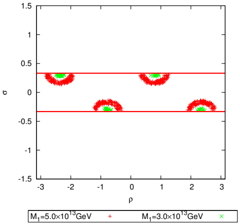
(NH)

$M_1 > 1.0 \times 10^{10}$GeV



(IH)

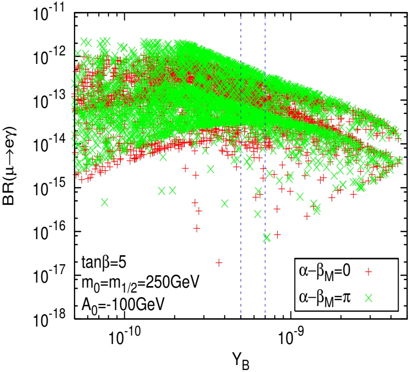
$M_1 > 7.0 \times 10^{12}$GeV

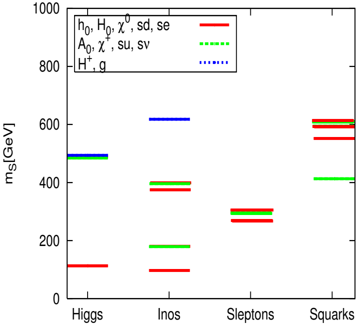


(QD)

$M_1 > 3.0 \times 10^{13}$GeV

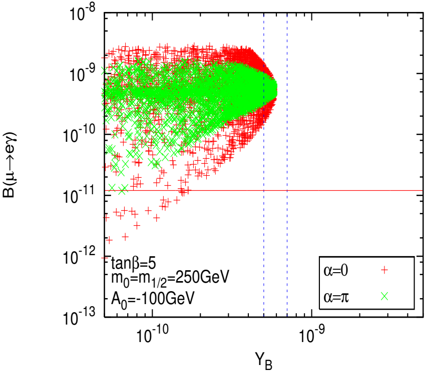
$B(\mu \to e\gamma)$ for NH

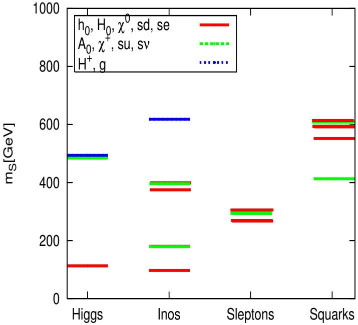




NH case ($m_1 = 0$, $m_2 \sim 0.008$eV, $m_3 \sim 0.05$eV),
$M_1 = 6.0 \times 10^{10}$GeV, $M_2 = 1.0 \times 10^{12}$GeV,
$\tan\beta = 5$, $m_0 = m_{1/2} = 250$GeV, $a_0 m_0 = -100$GeV

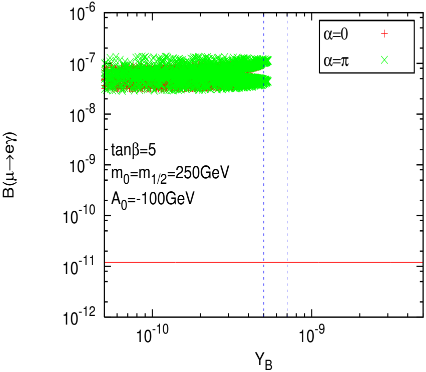
B($\mu \to e\gamma$) for IH

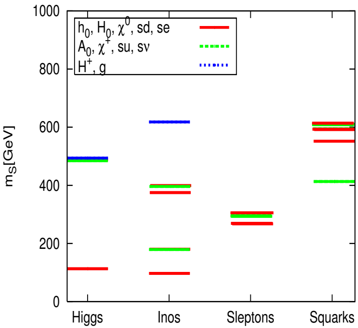




IH case ($m_1 \sim m_2 \sim 0.05$eV, $m_3 = 0$eV),
$M_1 = 7.0 \times 10^{12}$GeV, $M_2 = 4.0 \times 10^{13}$GeV,
$\tan\beta = 5$, $m_0 = m_{1/2} = 250$GeV, $a_0 m_0 = -100$GeV

$B(\mu \to e\gamma)$ for QD





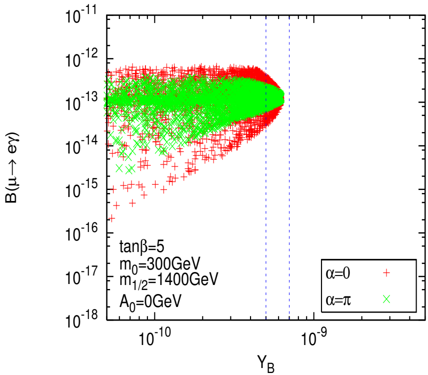
QD case ($m_1 = 0$, $m_2 \sim 0.008$eV, $m_3 \sim 0.05$eV),
$M_1 = 3.0 \times 10^{13}$GeV, $M_2 = 1.2 \times 10^{14}$GeV,
$\tan\beta = 5$, $m_0 = m_{1/2} = 250$GeV, $a_0 m_0 = -100$GeV

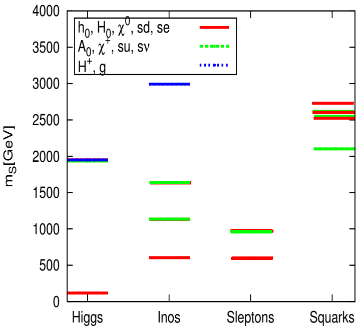
IH case

Hereafter, we focus on the IH case.
Even in the case where the M_3 contributions are decoupled, SUSY contributions to B($\mu \to e\gamma$) is so large that the present experimental constraint exclude the scenario with low SUSY spectrum.
There is two possibilities:

- Heavy SUSY spectrum case
- Y_N s.t. M_2 contributions are also suppressed

B($\mu \to e\gamma$) for IH with heavy SUSY





IH case ($m_1 \sim m_2 \sim 0.05$eV, $m_3 = 0$eV),
$M_1 = 7.0 \times 10^{12}$GeV, $M_2 = 4.0 \times 10^{13}$GeV,
$\tan\beta = 5$, $m_0 = 300$GeV, $m_{1/2} = 1400$GeV, $a_0 m_0 = 0$GeV

Texture zero

S. T. Petcov and T.S., in preparation

Now our model has no M_3 contributions

$$
\begin{aligned}
(Y_N^\dagger L Y_N)_{21} = {} & \frac{M_3}{v_u^2} \ln \frac{M_3}{M_X} (\mathbf{R}\sqrt{D_\nu} U^\dagger)^*_{32} (\mathbf{R}\sqrt{D_\nu} U^\dagger)_{31} \\
& + \frac{M_2}{v_u^2} \ln \frac{M_2}{M_X} (\mathbf{R}\sqrt{D_\nu} U^\dagger)^*_{22} (\mathbf{R}\sqrt{D_\nu} U^\dagger)_{21} \\
& + \frac{M_1}{v_u^2} \ln \frac{M_1}{M_X} (\mathbf{R}\sqrt{D_\nu} U^\dagger)^*_{12} (\mathbf{R}\sqrt{D_\nu} U^\dagger)_{11}
\end{aligned}
$$

Texture zero

S. T. Petcov and T.S., in preparation

Now our model has no M_3 contributions

$$(Y_N^\dagger L Y_N)_{21} = \frac{M_2}{v_u^2}\ln\frac{M_2}{M_X}(\mathbf{R}\sqrt{D_\nu}U^\dagger)^*_{22}(\mathbf{R}\sqrt{D_\nu}U^\dagger)_{21} + \frac{M_1}{v_u^2}\ln\frac{M_1}{M_X}(\mathbf{R}\sqrt{D_\nu}U^\dagger)^*_{12}(\mathbf{R}\sqrt{D_\nu}U^\dagger)_{11}$$

The second step is suppressing M_2 contributions

$\Rightarrow$

- $(\mathbf{R}\sqrt{D_\nu}U^\dagger)_{22} = 0$
- $(\mathbf{R}\sqrt{D_\nu}U^\dagger)_{21} = 0$

Texture zero

S. T. Petcov and T.S., in preparation

Now our model has no M_3 contributions

$$(Y_N^\dagger L Y_N)_{21} = \frac{M_2}{v_u^2} \ln \frac{M_2}{M_X} (\mathbf{R}\sqrt{D_\nu}U^\dagger)^*_{22} (\mathbf{R}\sqrt{D_\nu}U^\dagger)_{21} + \frac{M_1}{v_u^2} \ln \frac{M_1}{M_X} (\mathbf{R}\sqrt{D_\nu}U^\dagger)^*_{12} (\mathbf{R}\sqrt{D_\nu}U^\dagger)_{11}$$

The second step is suppressing M_2 contributions

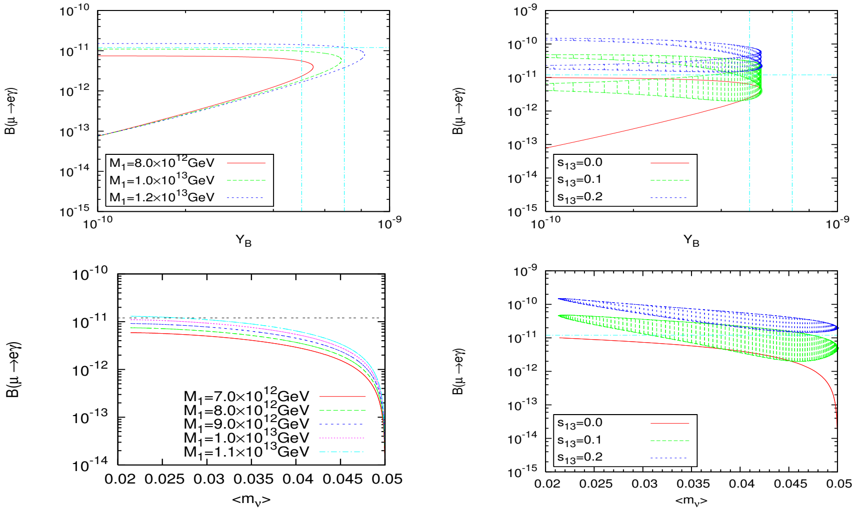
$\Rightarrow$

- $(\mathbf{R}\sqrt{D_\nu}U^\dagger)_{22} = 0 \;\Rightarrow \tan\omega = \tan\theta_{12} e^{-i\alpha/2}$
- $(\mathbf{R}\sqrt{D_\nu}U^\dagger)_{21} = 0 \;\Rightarrow \tan\omega = -\frac{c_{12} - s_{12}s_{13}e^{-i\delta}}{s_{12} + c_{12}s_{13}e^{-i\delta}} e^{-i\alpha/2}$

In both case, ω is related to the Majorana phase α

$\Rightarrow$ B($\mu \to e\gamma$), Y_B, and $\langle m_\nu \rangle$ are related to each other.

$\langle m_\nu \rangle$—Y_B—B$(\mu \to e\gamma)$

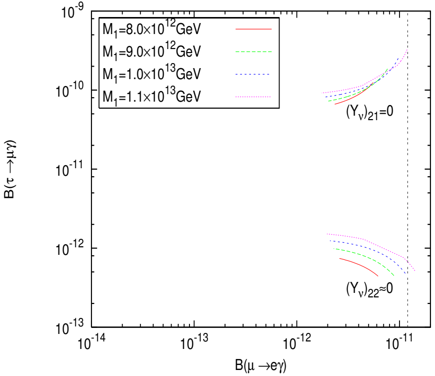


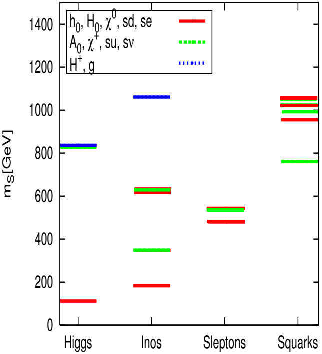
$(Y_N)_{21} = 0$ $(Y_N)_{22} = 0$

$s_{13} < 0.2$, $m_0 = m_{1/2} = 450$GeV, $a_0 m_0 = 0$, $\tan\beta = 5$

$\mu \to e\gamma$ and $\tau \to \mu\gamma$

The two models: $(Y_N)_{21} = 0$ and $(Y_N)_{22} = 0$ can be distinguished by the correlation between $\mu \to e\gamma$ and $\tau \to \mu\gamma$.





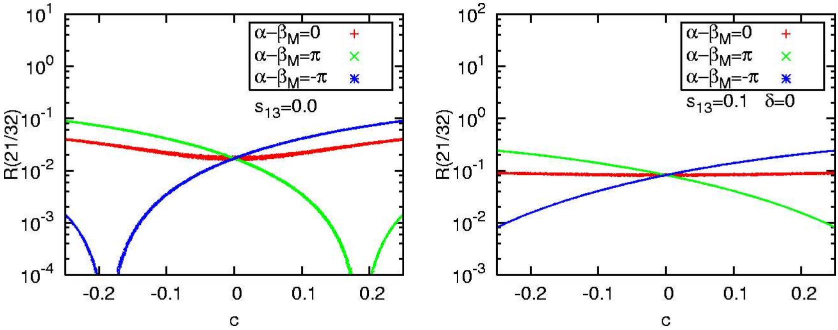
$s_{13} = 0.0$, $m_0 = m_{1/2} = 450\text{GeV}$, $a_0 m_0 = 0$, $\tan\beta = 5$

$5.0 \times 10^{-10} \leq Y_B \leq 7.0 \times 10^{-10}$

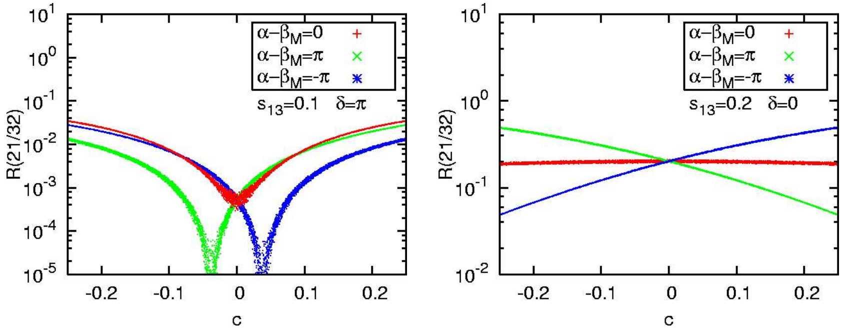
Summary

- If SUSY at $<$TeV is realized in nature, LHC is likely to provide some evidence.
- LFV is very powerful tool to explor the neutrino Yukawa sector in MSSM with seesaw scenario.
- Both low energy CP phases (α, β_M and δ) and high energy CP phases (phases in **R**) contribute to LFV processes.
- The correlation between $\mu \to e\gamma$ and $\tau \to \mu\gamma$ may give information about high energy phases.

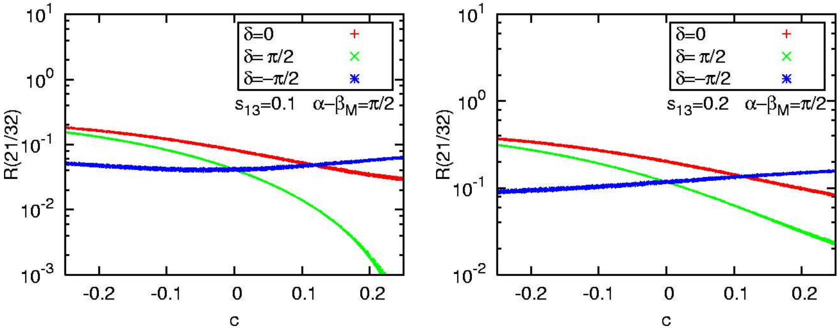
Figures for NH



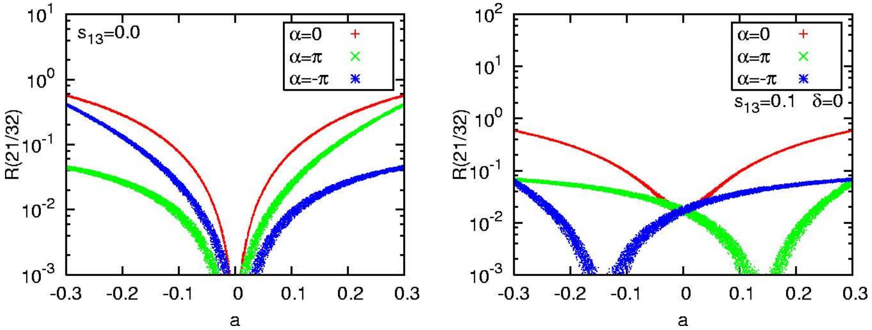
Figures for NH



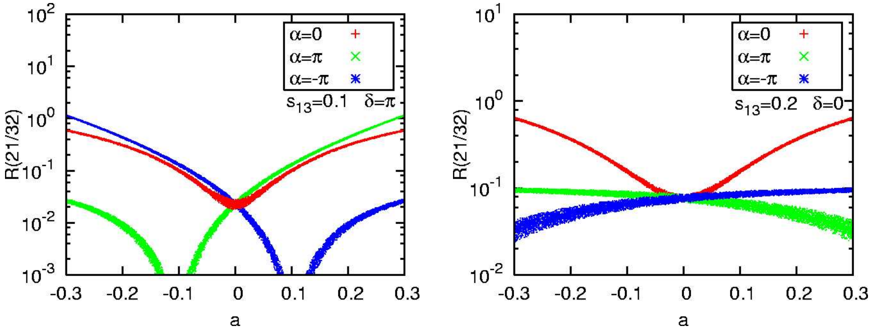
Figures for NH



Figures for IH



Figures for IH



Figures for IH