Phenomenological implications of charged lepton flavour and CP violation

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Introduction

In the Standard Model (Weinberg's "model of leptons"), the lepton number is conserved for each generation (perturbatively).

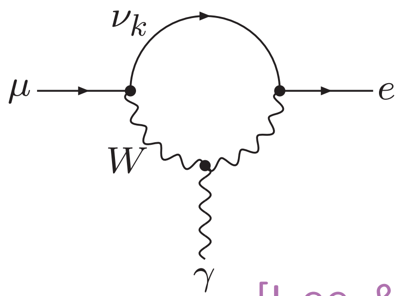
- One Higgs doublet, massless (Weyl) neutrinos.

Lepton flavour is known to be violated.

- ν oscillation $\rightarrow$ mass^2 splittings & mixing angles determined.

Tiny ν masses (splittings)

$$\Rightarrow \quad \mathrm{B}(\mu \to e\,\gamma) \simeq 10^{-54}\,.$$



[Lee & Shrock, 1977]

Charged LFV (observable in near future) = signal of Beyond the SM.

Introduction

Great experimental improvements in recent years:

- Higgs boson found: $m_h \simeq 126\,\text{GeV}$ [ATLAS/CMS].
- SUSY limits raised: $m_{\tilde{g}} > 1.4\,\text{TeV}$, $m_{\tilde{q}} > 1.8\,\text{TeV}$ [ATLAS/CMS].
- $B_s \to \mu^+ \mu^-$ observed: $\mathsf{B} \simeq 2.9 \times 10^{-9}$ [LHCb/CMS].
- ν mixing angle θ_{13} is measured: $\sin^2 2\theta_{13} \simeq 0.089$ [Daya Bay].
- $\mu \to e\,\gamma$ limit improved: $\mathsf{B} < 5.7 \times 10^{-13}$ [MEG].

  ...

No BSM signal so far ⇒ stronger constraints are given in many places.

Questions:

- How much space is remaining for sizable cLFV?
- What are promising observables?

Introduction

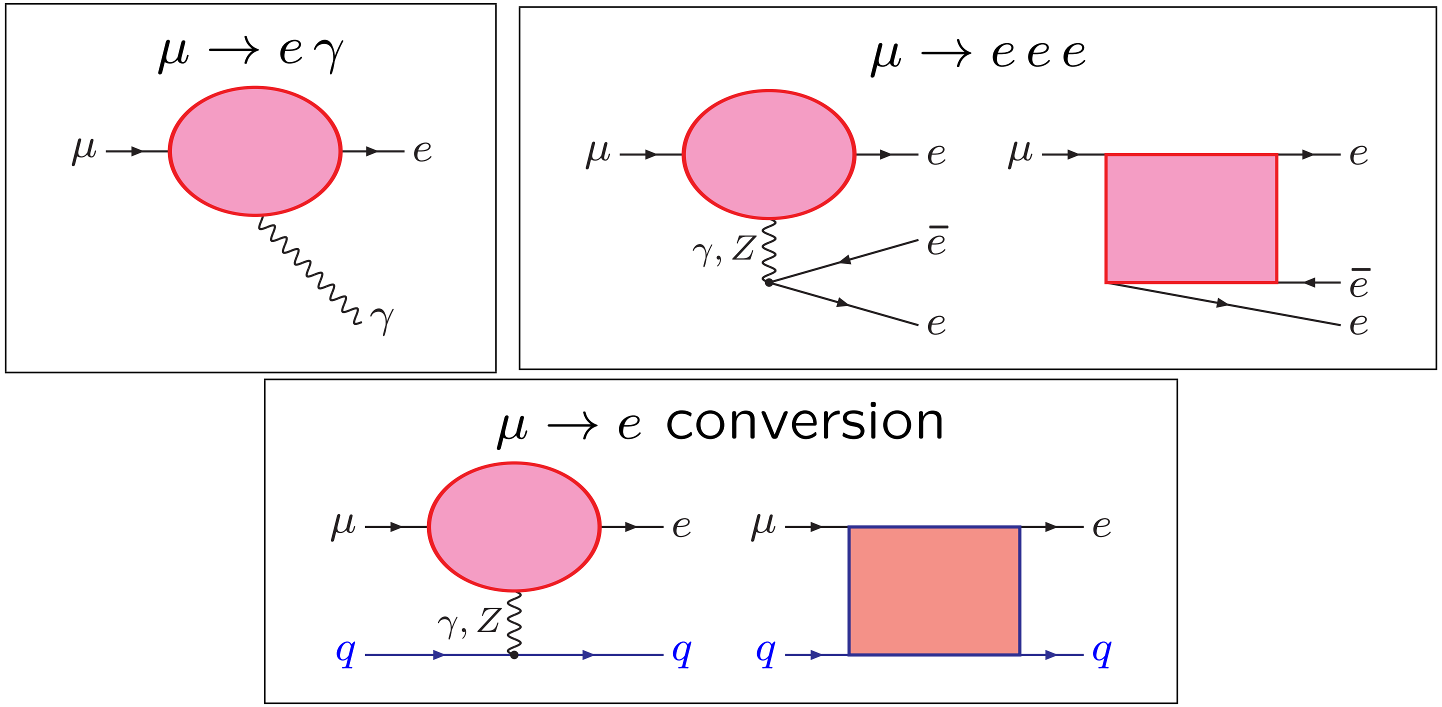
cLFV processes:

	$\mu \to e$	$\tau \to \mu$	$\tau \to e$
γ	$\mu \to e\,\gamma$	$\tau \to \mu\,\gamma$	$\tau \to e\,\gamma$
$\ell\,\bar{\ell}$	$\mu \to e\,e\,e$	$\tau \to \mu\,\mu\,\mu$	$\tau \to e\,e\,e$
		$\tau \to \mu\,e^{+}\,e^{-}$	$\tau \to e\,\mu^{+}\,\mu^{-}$
$q\,\bar{q}$	$\mu\,N \to e\,N$	$\tau \to \mu$ hadrons	$\tau \to e$ hadrons

- Z, h decays: $Z \to e^{\pm}\,\mu^{\mp}$, $h \to \mu^{\pm}\,\tau^{\mp}$, $\cdots$
- $\Delta LF > 1$: $\mu^{+}\,e^{-} \leftrightarrow \mu^{-}\,e^{+}$, $\tau^{+} \to \mu^{-}\,e^{+}\,e^{+}$, $\cdots$
- LFV & FCNC: $K_L \to \mu\,e$, $B_s \to \tau\,\mu$, $\cdots$

Introduction

BSM models introduce new particles and interactions.



Effects on cLFV are model/process dependent.

Introduction

Examples shown in the following:

- SUSY type I seesaw model
- Littlest Higgs model with T-parity
- Radiative neutrino mass model

SUSY type I seesaw model

Supersymmetry: still atractive candidate of BSM (GUT, DM, $\cdots$).

$$\begin{aligned}\text{MSSM} &= \text{SM} + \text{SUSY (superpartners, interactions)} \\ &\quad + \text{extra Higgs (type-II 2HDM)} + \text{SUSY breaking}.\end{aligned}$$

SUSY flavour problem [Ellis & Nanopoulos, 1982]

- In geneal MSSM (MSSM-124) $\rightarrow$ quark/lepton flavour violations in SUSY breaking uncontrolable.
  - ▷ Squark/slepton mass matrices,
  - ▷ Trilinear scalar couplings ("A"-terms).

Motivates flavour-blind SUSY breaking (mediation) mechanisms

- minimal supergravity (mSUGRA, CMSSM),
- gauge mediation, anomaly mediation, $\cdots$

SUSY Type I seesaw model

High-energy superpotential: Yukawa couplings & ν_R Majorana masses.

$$W^{[\text{high}]}_{\text{lepton}} = Y_E^{ij} E_i^c L_j H_1 + Y_N^{ij} N_i^c L_j H_2 + \frac{1}{2} M_\nu^{ij} N_i^c N_j^c \,.$$

Low-energy effective superpotential: $N_i^c \ni \nu_{Ri}^c$ integrated out.

$$W^{[\text{low}]}_{\text{lepton}} = Y_E^{ij} E_i^c L_j H_1 - \frac{1}{2} \kappa_\nu^{ij} (L_i H_2)(L_j H_2) \,.$$

- Seesaw relation (tree level): $\kappa_\nu = Y_N^{\mathbf{T}} M_\nu^{-1} Y_N$.
- Light neutrino mass matrix: $m_\nu^{ij} = -\kappa_\nu^{ij} \langle h_2 \rangle^2$.

Parameter counting

- 9 in κ_ν^{ij}: 3 masses, 3 mixing angles & 3 phases
  - ▹ 2 mass^2 splittings & 3 mixing angles measured.
- 18 in M_ν and Y_N. $\Rightarrow$ 9 free parameters.

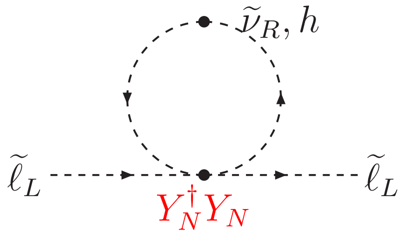
SUSY Type I seesaw model

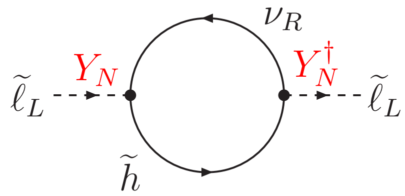
Soft SUSY breaking terms

$$
\begin{aligned}
-\mathcal{L}_{\text{soft}}^{[\text{high}]} = & (m_L^2)_{ij}\tilde{\ell}_{Li}^{\dagger}\tilde{\ell}_{Lj} + (m_E^2)_{ij}\tilde{e}_{Ri}^{*}\tilde{e}_{Rj} + (m_N^2)_{ij}\tilde{\nu}_{Ri}^{*}\tilde{\nu}_{Rj} \\
& + \left(A_E^{ij}\tilde{e}_{Ri}^{*}\tilde{\ell}_{Lj}h_1 + A_N^{ij}\tilde{\nu}_{Ri}^{*}\tilde{\ell}_{Lj}h_2 + \frac{1}{2}\tilde{m}_\nu^{2ij}\tilde{\nu}_{Ri}^{*}\tilde{\nu}_{Rj}^{*} + \text{H.c.} \right) \\
& + (\text{squarks}) + (\text{Higgs masses}) + (\text{Gaugino masses}).
\end{aligned}
$$

mSUGRA scenario:

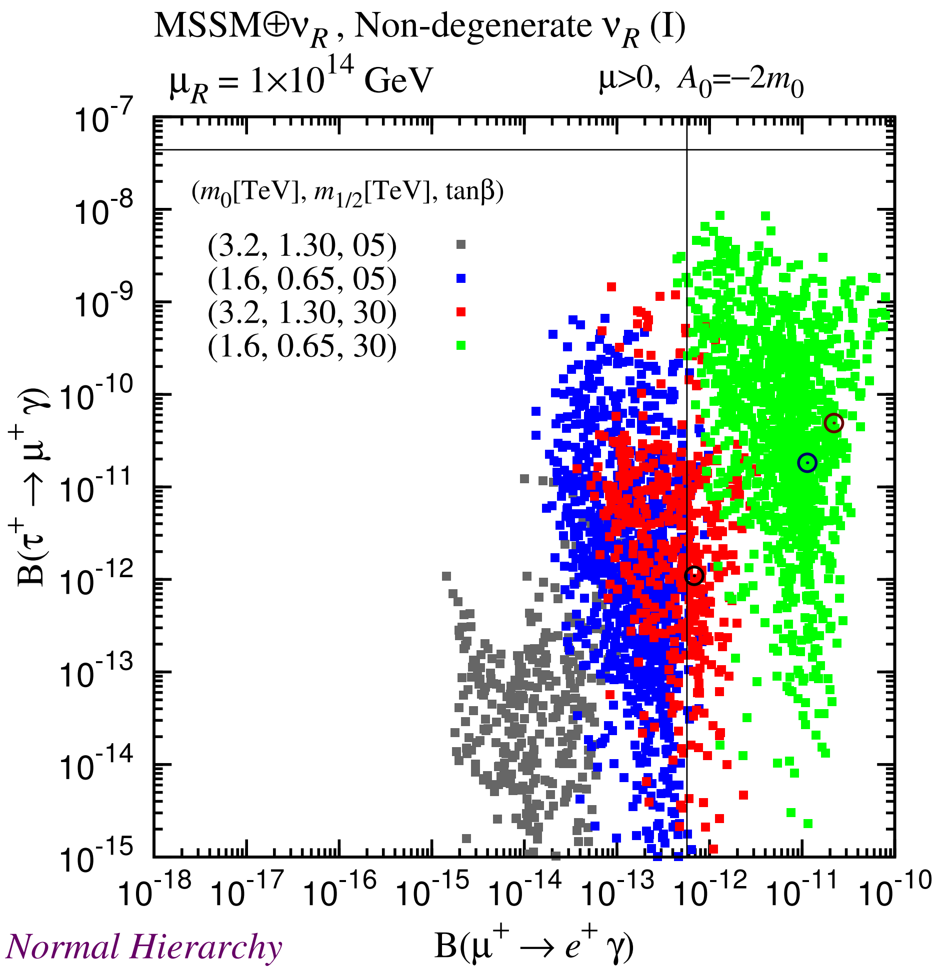
- $m_L^2 = m_E^2 = m_0\mathbf{1}$, $A_E = A_0 Y_E$: no cLFV at GUT scale μ_G.
- Below μ_G, flavour dependent quantum corrections to the slepton mass matrices are induced by Yukawa interactions [Borzumati & Masiero, 1986].
- Y_N mainly affect flavour mixing in m_L^2.



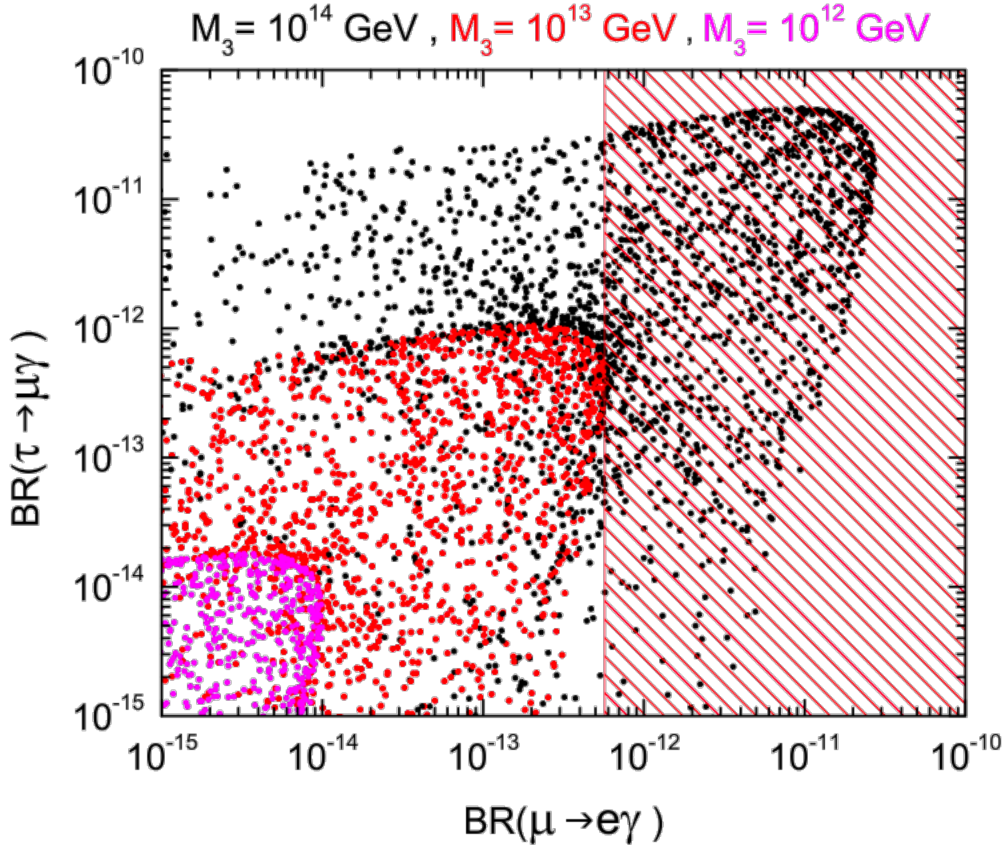


SUSY Type I seesaw model

SUSY parameters fixed, ν_R parameters varied:



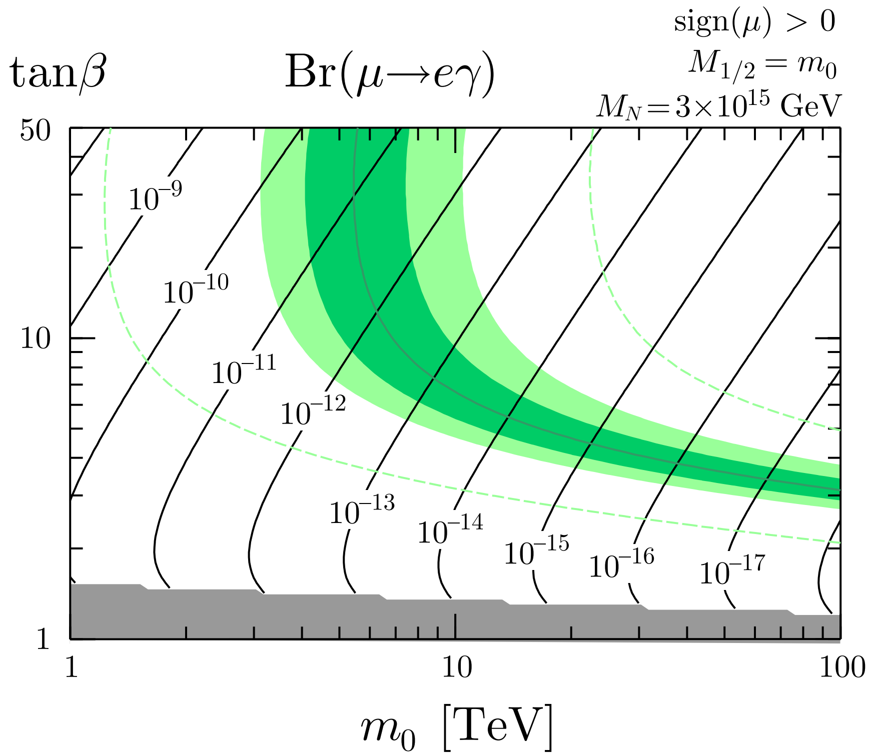
[Goto *et al.*, FLASY2013]



[Joaquim, ICHEP2014]

SUSY Type I seesaw model

ν_R parameters fixed, SUSY parameters varied:



[Moroi, Nagai & Yanagida, 1305.7357]

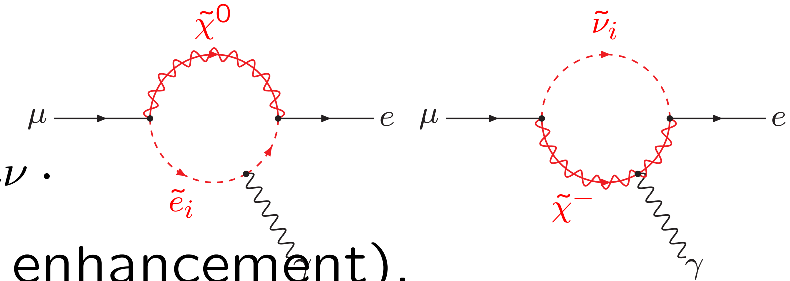
- $M_{\nu_R} \propto \mathbf{1} \Rightarrow \tau$ LFV small under $\mu \to e\,\gamma$ constraint.

SUSY Type I seesaw model

Dipole dominance

- In a wide class of SUSY models/parameter regions, dominant contribution to cLFV processes appears in

$$\mathcal{O}_{\gamma L,R} = \bar{\ell}' \sigma^{\mu\nu} \ell_{L,R} F_{\mu\nu} \,.$$



  ▷ Large chirality flipping sources ($\tan\beta$ enhancement).

⇒ Relations among branching fractions derived:

$$\frac{\mathrm{B}(\mu \to e\,e\,e)}{\mathrm{B}(\mu \to e\,\gamma)} \simeq \frac{\alpha}{3\pi}\left[\log\frac{m_\mu^2}{m_e^2} - \frac{11}{4}\right] \simeq 6\times 10^{-3}\,,$$

$$\frac{\mathrm{B}(\mu\,\mathrm{Al} \to e\,\mathrm{Al})}{\mathrm{B}(\mu \to e\,\gamma)} \simeq 2\times 10^{-3} \quad \text{(depends on nucleus)}\,,$$

$$\frac{\mathrm{B}(\tau \to \mu\, e^+ e^-)}{\mathrm{B}(\tau \to \mu\,\gamma)} \simeq \frac{\alpha}{3\pi}\left[\log\frac{m_\tau^2}{m_e^2} - 3\right] \simeq 10^{-2}\,, \qquad etc.$$

Littlest Higgs model with T-parity (LHT)

In order to suppress radiative corrections to the Higgs boson mass...

- Spontaneously broken global symmetry is introduced; SM Higgs boson is accommodated as a pseudo Nambu-Goldstone boson.
- Gauge symmetry is arranged so that one-loop correction to the Higgs boson mass is suppressed.

Littlest Higgs: $SU(5)/SO(5)$ nonlinear σ model [Arkani-Hamed *et al.*, 2002]

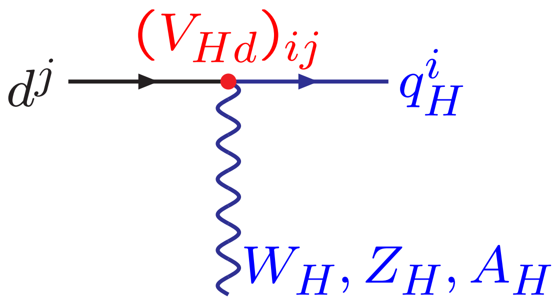
global:	$SU(5)$	$\overset{f}{\Rightarrow}$	$SO(5)$
	$\cup$		$\cup$
gauged:	$[SU(2)\times U(1)]_1 \times [SU(2)\times U(1)]_2$	$\overset{f}{\Rightarrow}$	$SU(2)\times U(1)$ SM electroweak

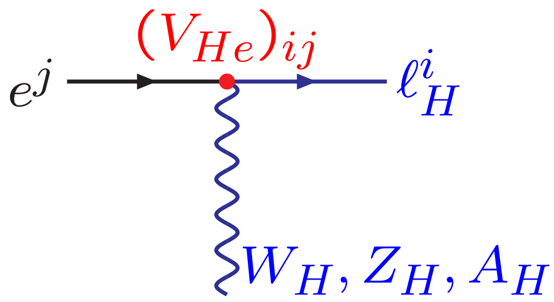
- NG bosons in SU(5)/SO(5) $\supset$ SM Higgs doublet.
- T-parity: $[SU(2)\times U(1)]_1 \overset{\mathrm{T}}{\Longleftrightarrow} [SU(2)\times U(1)]_2 \Rightarrow (g,g')_1 = (g,g')_2$.

LHT

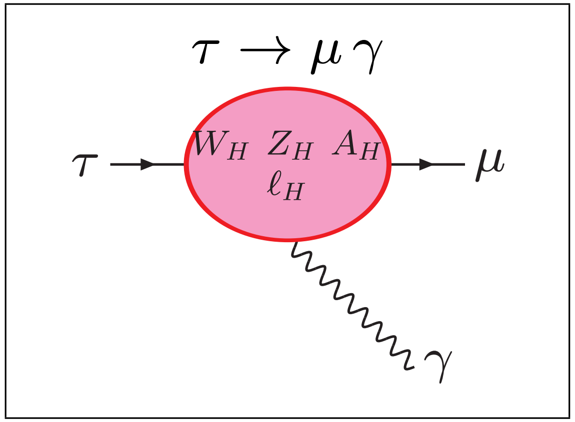
T-even	$\Leftrightarrow$	T-odd
$W,\ Z,\ \gamma$ $\begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$ $\begin{matrix} u_R^i \\ d_R^i \end{matrix}$ $\begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$ $\begin{matrix} \nu_R^i \\ e_R^i \end{matrix}$ T_+	$\Leftrightarrow$	$W_H,\ Z_H,\ A_H$ $\begin{pmatrix} u_{HL}^i \\ d_{HL}^i \end{pmatrix}$ $\begin{pmatrix} u_{HR}^i \\ d_{HR}^i \end{pmatrix}$ $\begin{pmatrix} \nu_{HL}^i \\ e_{HL}^i \end{pmatrix}$ $\begin{pmatrix} \nu_{HR}^i \\ e_{HR}^i \end{pmatrix}$ T_-

- $T_\pm$: "top partners". Cancels top one-loop correction to Higgs mass.
- Masses of T-odd particles and the "top partners" $= O(f) = O(\text{TeV})$.
- Mixing matrices $V_{Hd} V_{He}$: independent of CKM, PMNS.



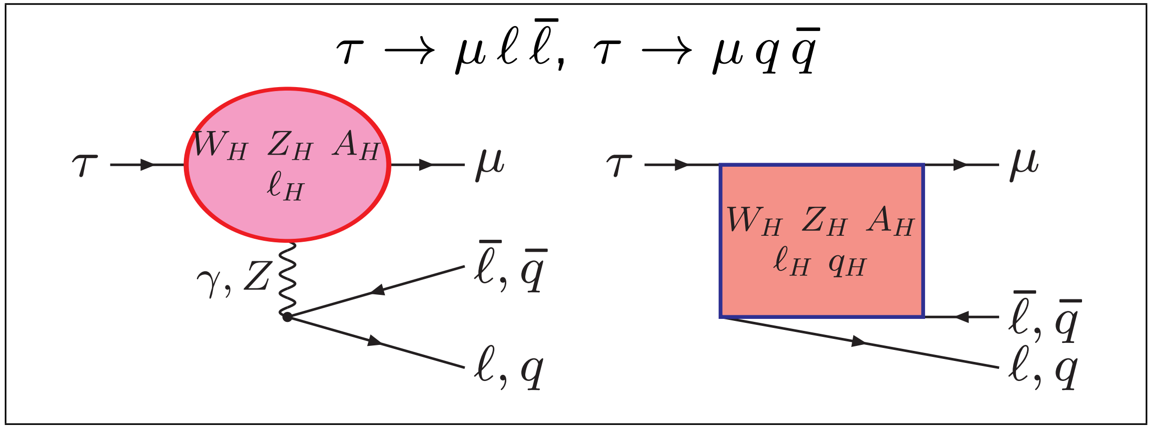


LFV in LHT



$\Updownarrow$

$\mu \to e\,\gamma$

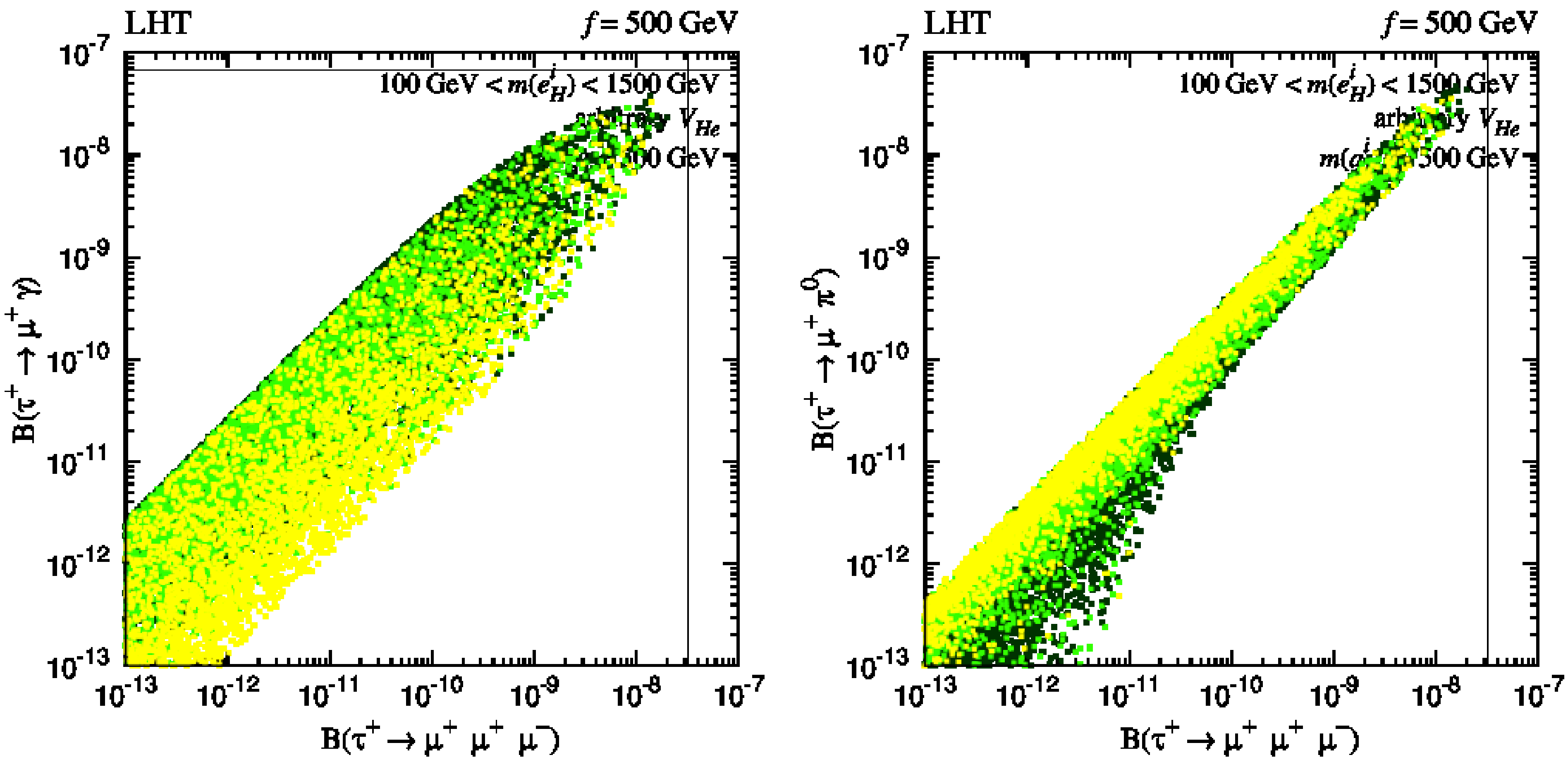


$\Updownarrow$

$\mu \to e\,e\,e$, $\mu - e$ conversion

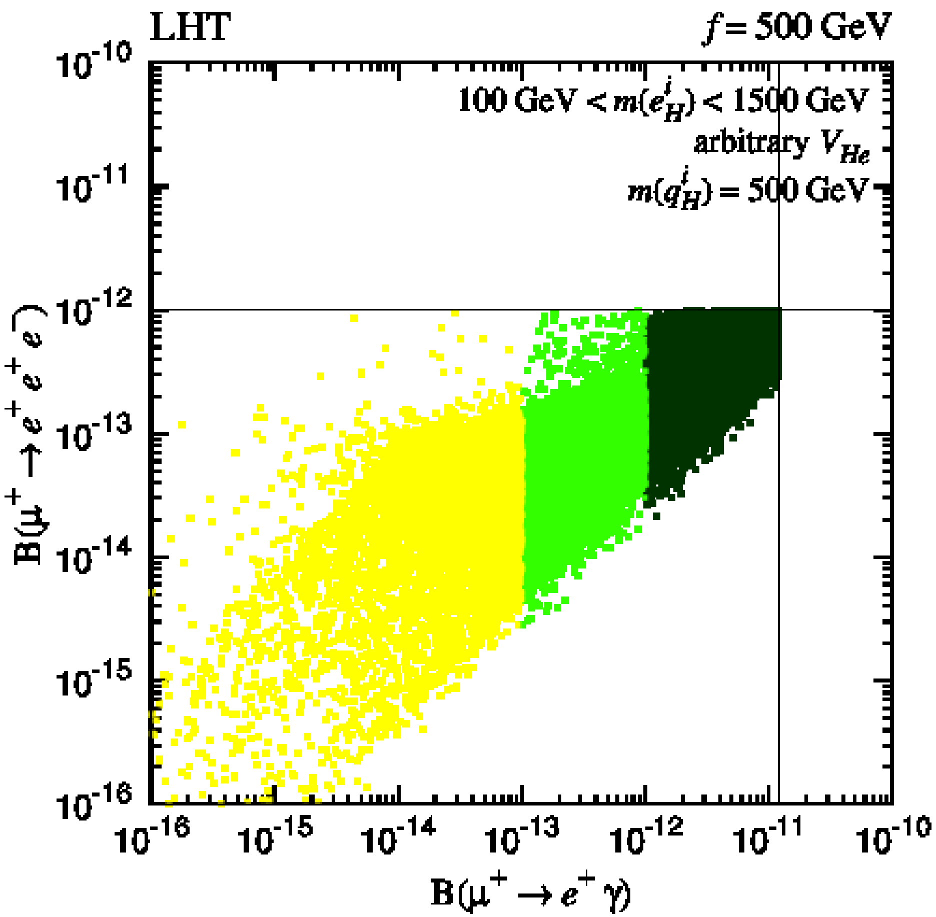
- LFV $\Leftarrow$ T-odd particle loops only.
- Interactions of W_H, Z_H, A_H and T-even (SM) quarks/leptons are left-handed only.
  - ▷ $\tau_R \to \mu_L\,\gamma$ are relatively small
    - ∗ $\mathrm{B}(\tau \to \mu\,\gamma) \sim \mathrm{B}(\tau \to \mu\,\mu\,\mu)$ etc. (cf. SUSY model: $\frac{\mathrm{B}(\tau\to\mu\,\mu\,\mu)}{\mathrm{B}(\tau\to\mu\,\gamma)} \approx \frac{1}{450}$)

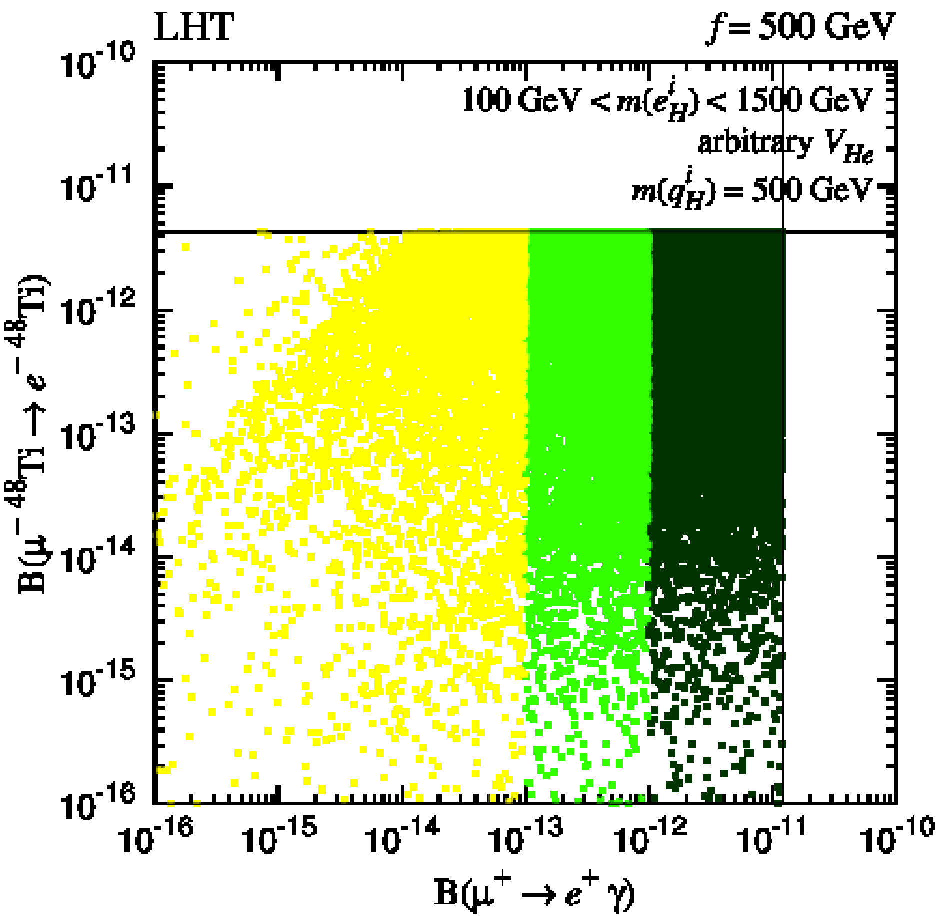
LFV in LHT: $\tau \to \mu$



[Goto, Okada & Yamamoto, '11]

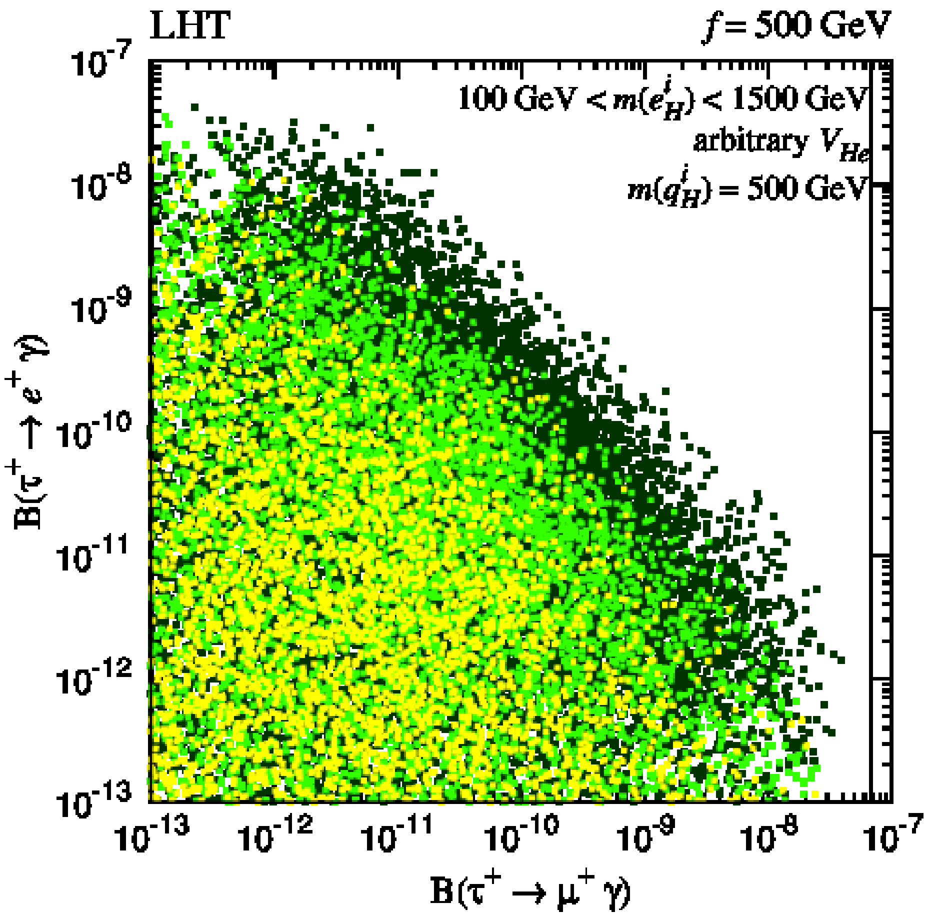
LFV in LHT: $\mu \to e$



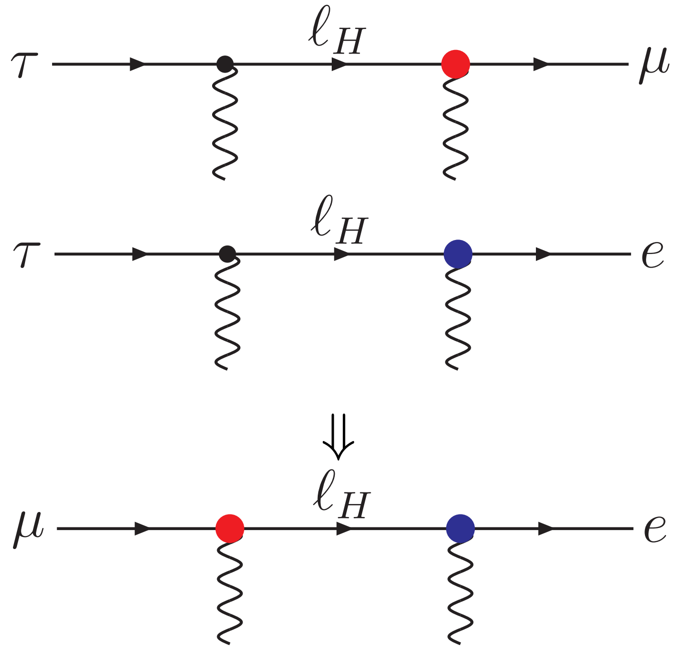


Updated limit: $\mathrm{B}(\mu \to e\,\gamma) < 5.7 \times 10^{-13}$ [MEG, 1303.0754].

LFV in LHT



- The region where both $\tau \to \mu$ and $\tau \to e$ are large is excluded due to the constraint by $\mu \to e$.

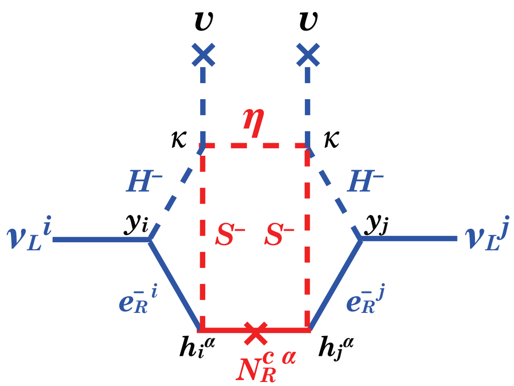


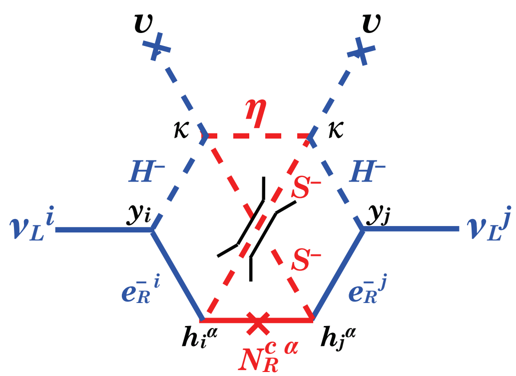
- Similar in SUSY case.

Three-loop neutrino mass model

[Aoki, Kanemura & Seto, 0807.0361]

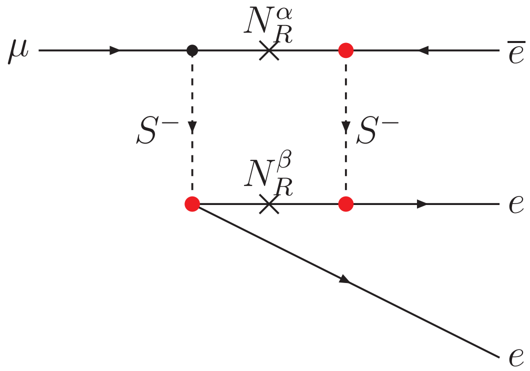
- Neutrino masses $\Leftarrow$ higher loops.
- $\sim$ TeV scale new particles:
  - ▷ extra Higgs doublet,
  - ▷ $SU(2)$ singlet scalars $S^{\pm}$, η^0,
  - ▷ right-handed neutrinos $N_R^{1,2}$.
- $Z_2 \times Z_2$ discrete symmetry is arranged so that one- and two-loop contributions to ν masses are forbidden.

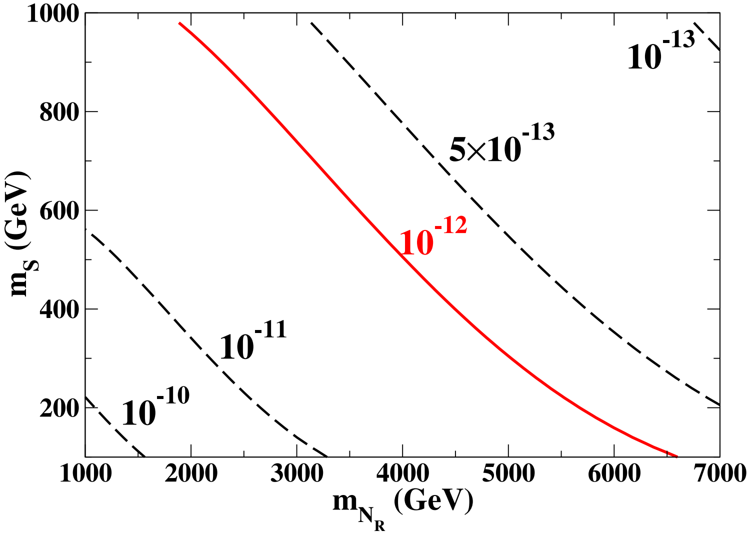




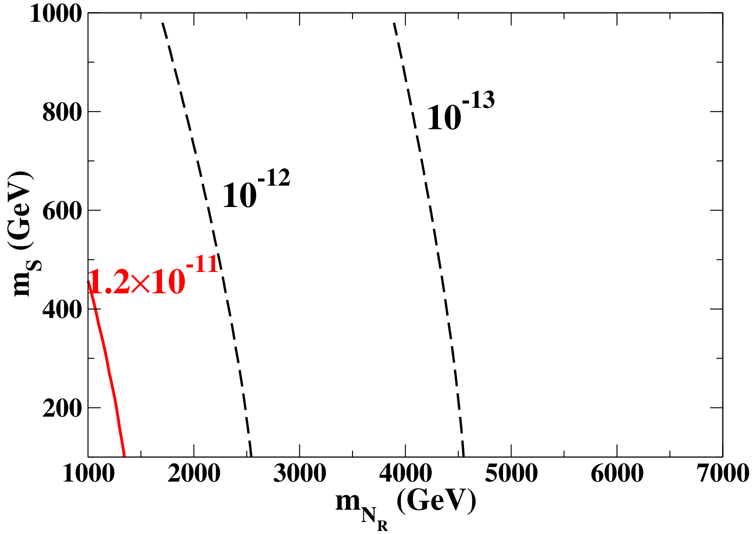
Three-loop neutrino mass model

- $\bar{e}^c_R N^\alpha_R S^+$ coupling $\sim O(1) \gg \mu$ and τ couplings.
- $\mu \to e\,e\,e$ (only) enhanced.





$\mathrm{B}(\mu \to e\,e\,e)$



$\mathrm{B}(\mu \to e\,\gamma)$

[Aoki, Kanemura & Yagyu, 1102.3412]

Conclusion

Various possibilities in charged lepton flavour violation observables are widely open.

- Many BSM models predict LFV signals measurable in near future.
- Predictions are highly model dependent.
  - ▷ $\mu \to e$ vs. $\tau \to \mu$ vs. $\tau \to e$.
  - ▷ Radiative vs. leptonic vs. hadronic.

Experiments play complementary roles to each other.

- Measurements of many observables are necessary to understand flavour structure in the lepton sector.

Waiting for "First observation of cLFV in ???".