Charged Lepton-Flavor Violation in Beyond-Standard Models

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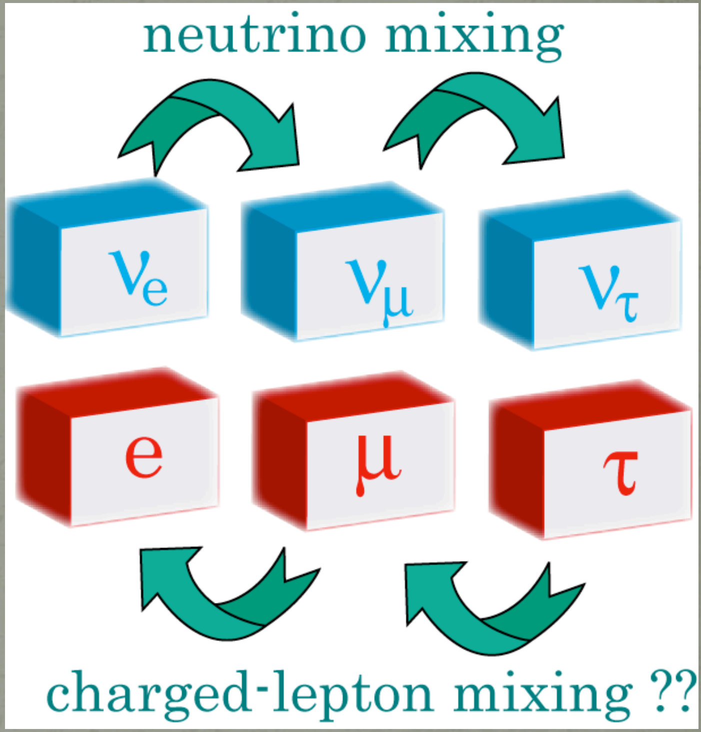
1, Introduction

Charged Lepton-Flavor Violation (cLFV)

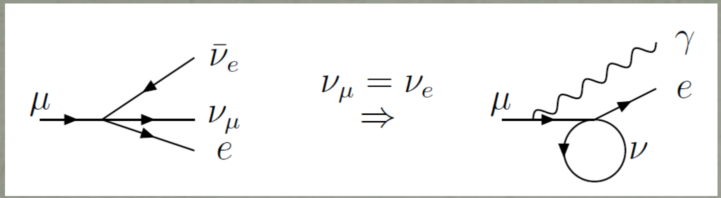
- μ to e
  1. $\mu \rightarrow e\gamma$
  2. $\mu \rightarrow eee$
  3. $\mu - e$ conversion in nuclei

- τ to μ and τ to e
  1. $\tau \rightarrow \mu/e\gamma$
  2. $\tau \rightarrow \mu/e + ll$
  3. $\tau \rightarrow \mu/e + \text{hadron}$



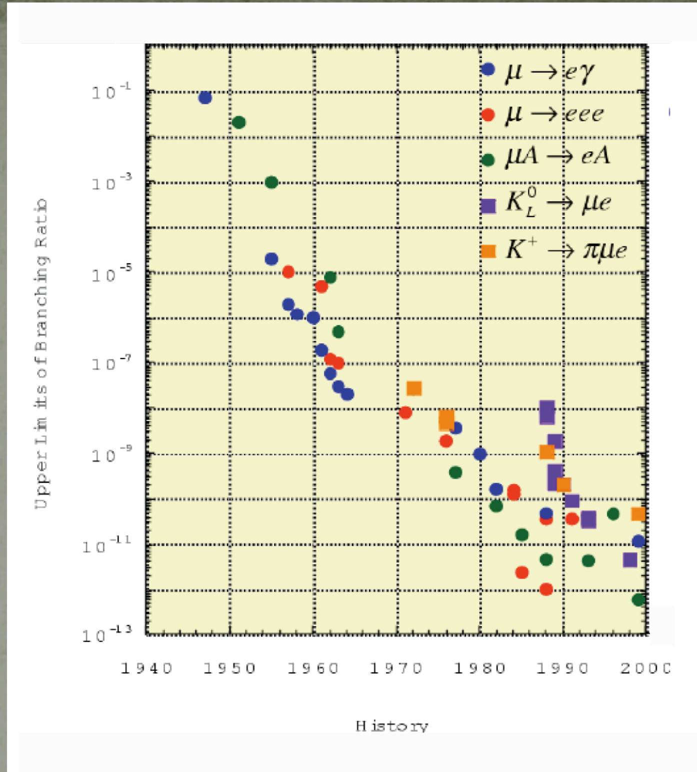
Why not cLFV processes are discovered ?
Now it is a big mystery in particle physics.

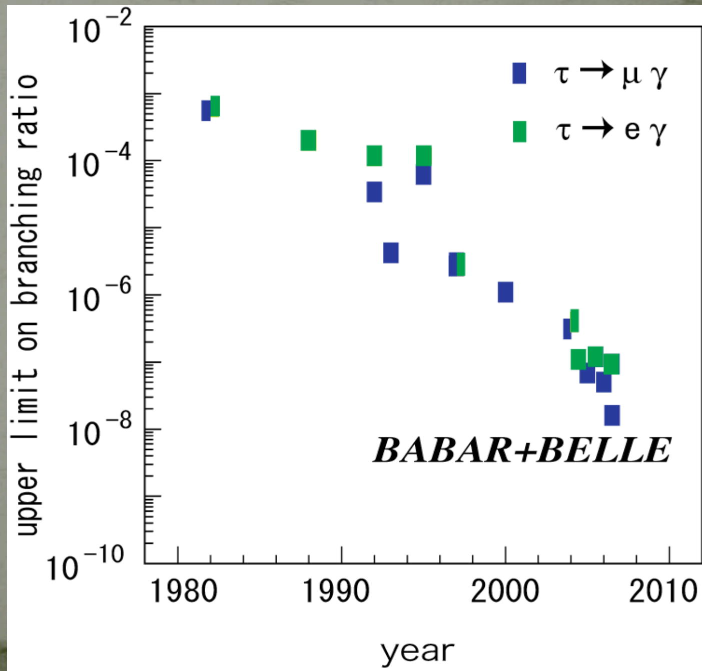
- On'60, two-neutrino hypothesis was proposed so that lepton flavors conservation suppresses $\mu \to e\gamma$.



- In the SM, neutrinos are massless, and then, lepton flavors are automatically conserved.

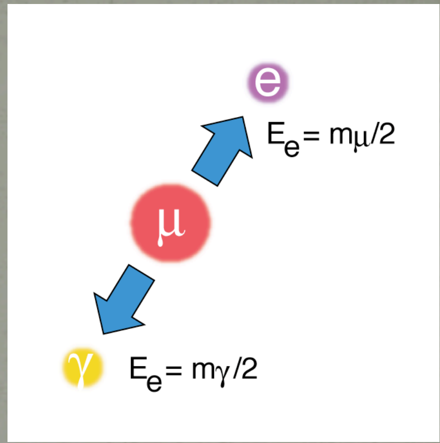
- On '98, the neutrino oscillation was discovered at SuperK. It was found that lepton-flavor conservation is not exact in nature.





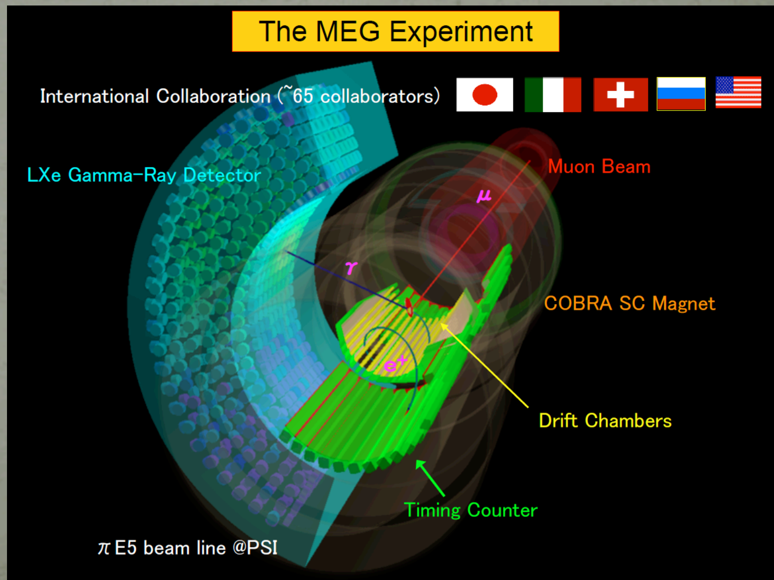
Search for μ to e γ (MEG kicks off !)

- Current bound:
  $Br(\mu \to e\gamma) < 1.2 \times 10^{-11}$ (MEGA, 99')

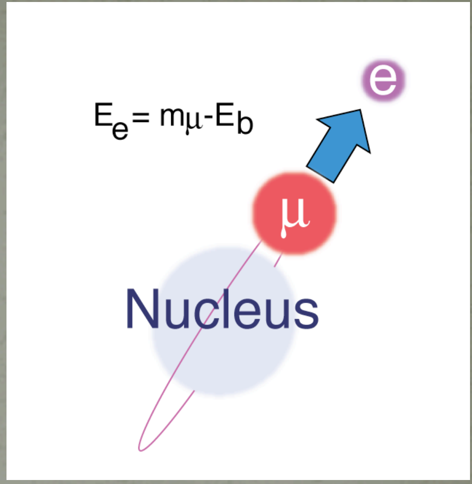


From Mori-san,

- MEG experiment at PSI is being started now.
- A successful physics run for 5-6 months brings us to (7-8) * 10^{-13} sensitivity.
- A goal of MEG (Phase I) is (1-2) * 10^{-13} after another two years.
- Further down to 1* 10^{-14} (?) after possible upgrades (Phase II).



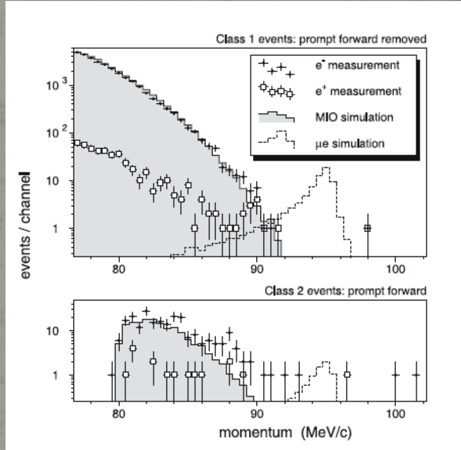
Search for μ-e conversion in nuclei



- Conversions are coherent processes and the rates are larger for larger nuclei.

$$R_{\mu e}(N) \equiv \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu_\mu N')}$$

- Monochromatic electron from muonic atom is signal ($E_e = m_\mu - E_b$), and BGs are quite suppressed.



(Au case in SINDRUM II)

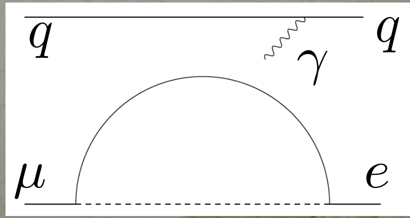
- Current bounds:

$R_{\mu e}(\mathrm{Ti}) < 6 \times 10^{-13}$ (SINDRUM II, 93')

$R_{\mu e}(\mathrm{Au}) < 7 \times 10^{-13}$ (SINDRUM II, 00')

- If photon-penguin process is dominant (typical SUSY cases),

$R_{\mu e}(\mathrm{Ti}) \simeq 4 \times 10^{-3} Br(\mu \to e\gamma)$



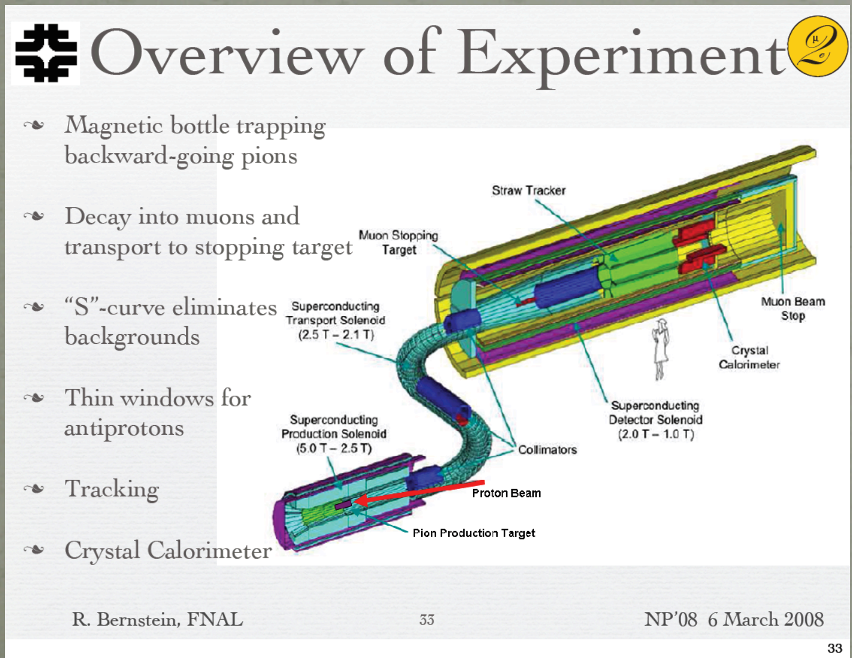
(photon-penguin)

Search for μ-e conversion in nuclei (plan)

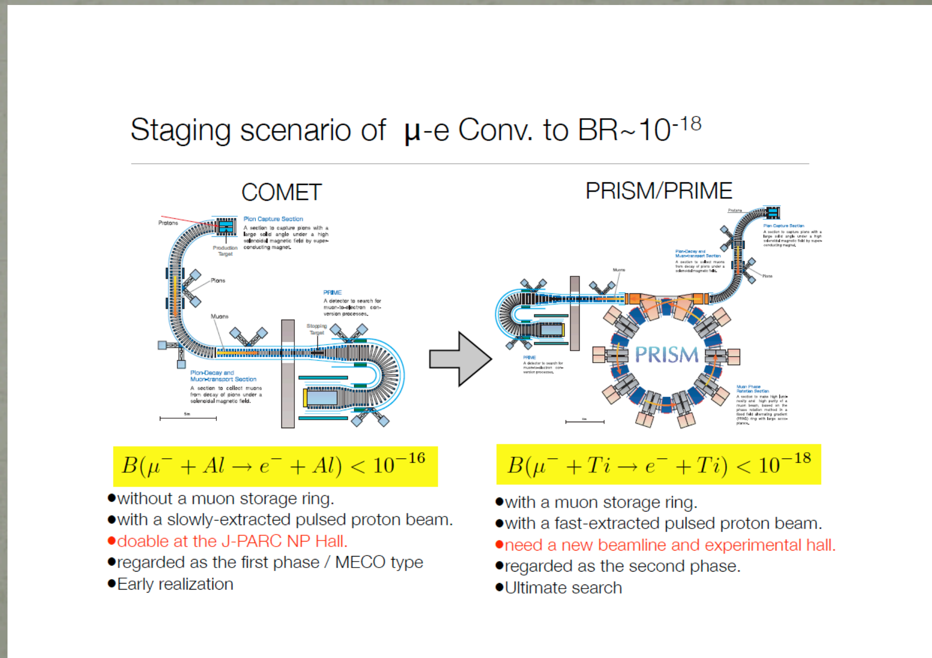
Next experiments have to aim at Rμe ~10^{-16}.

- Mu2e (Fermilab): $R_{\mu e}(\mathrm{Al}) \sim 6 \times 10^{-17}$
- COMET (J-parc): $R_{\mu e}(\mathrm{Al}) \sim 5 \times 10^{-17}$
- PRISM/PRIME (J-parc): $R_{\mu e}(\mathrm{Ti}) \sim 10^{-18}$

  Muon storage ring.



(From Prebys's talk in NP08)



(From Kuno-san's talk)

Search for τLFV processes

Tau-lepton flavor violation search is being performed by Belle and BaBar, and the bounds on branching ratios reach to ~$10^{-(7\text{-}8)}$. (Hayashii-san will talk.)

τ^- mode	Belle $\mathcal{B}, 10^{-8}$	Belle $\int L dt$, fb^{-1}	BaBar $\mathcal{B}, 10^{-8}$	BaBar $\int L dt$, fb^{-1}
$\mu^-\gamma$	4.5	535	6.8	232
$e^-\gamma$	12	535	11	232
$e^-e^-e^+$	3.6	535	4.9	376
$e^-\mu^-\mu^+$	4.1	535	6.6	376
$e^+\mu^-\mu^-$	2.3	535	4.6	376
$\mu^-e^-e^+$	2.7	535	5.0	376
$\mu^-\mu^-\mu^+$	3.2	535	6.7	376
$\mu^+e^-e^-$	2.0	535	2.7	376

τ^- mode	Belle $\mathcal{B}, 10^{-8}$	Belle $\int L dt$, fb^{-1}	BaBar $\mathcal{B}, 10^{-8}$	BaBar $\int L dt$, fb^{-1}
$e^-\pi^0$	8.0	401	13	339
$e^-\eta$	9.2	401	16	339
$e^-\eta'$	16	401	24	339
$\mu^-\pi^0$	12	401	11	339
$\mu^-\eta$	6.5	401	15	339
$\mu^-\eta'$	13	401	14	339

From Epifanov's talk in Lake Louise Winter Istutute (08')

Search for τLFV processes (contd)

τ^- mode	Belle		BaBar		CLEO	
	$\mathcal{B}$, 10^{-8}	$\int Ldt$, fb^{-1}	$\mathcal{B}$, 10^{-8}	$\int Ldt$, fb^{-1}	$\mathcal{B}$, 10^{-8}	$\int Ldt$, fb^{-1}
$e^- \rho^0$	6.3	543	–	–	200	4.79
$e^- K^*(892)^0$	7.8	543	–	–	510	4.79
$e^- \bar{K}^*(892)^0$	7.7	543	–	–	740	4.79
$e^- \phi$	7.3	543	–	–	690	4.79
$e^- \omega$	18	543	11	384	–	–
$\mu^- \rho^0$	6.8	543	–	–	630	4.79
$\mu^- K^*(892)^0$	5.9	543	–	–	750	4.79
$\mu^- \bar{K}^*(892)^0$	10	543	–	–	750	4.79
$\mu^- \phi$	13	543	–	–	700	4.79
$\mu^- \omega$	8.9	543	10	384	–	–

Charged Lepton-Flavor Violation in Beyond-Standard Models

cLFVs in SM with m_ν and BSM

- Neutrino mass terms are LFV, however, cLFV processes are suppressed so much due to the GIM mechanism even after they are introduced in the SM.

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^\star_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W}\right|^2 < 10^{-54}$$

where U is PMNS matrix and $\Delta m^2_{ij} = m^2_{\nu i} - m^2_{\mu j}$.

- cLFVs are sensitive to physics beyond SM (BSM) at TeVs.

$$\mu\text{LFVs: } \mathcal{L} = \frac{m_\mu}{\Lambda^2_\star}\bar{e}(\sigma\cdot F)\mu + \frac{1}{\Lambda^2_\star}\bar{e}\mu\bar{e}e + \frac{1}{\Lambda^2_\star}\bar{e}\mu\bar{q}q$$

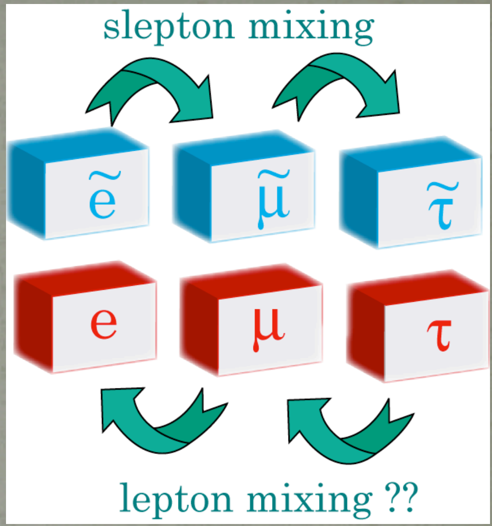
$$\Rightarrow Br(\mu \to e\gamma),\ Br(\mu \to 3e),\ R_{\mu e} \sim (m_W/\Lambda)^4$$

Λ_* should be larger than ~$10^{(5\text{-}6)}$ GeV.
But, real physical scale is usually smaller than it due to

- flavor symmetry breaking
- loop suppression

cLFVs in SUSY SM

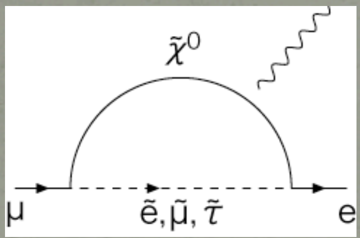
- SUSY breaking mass terms for SUSY particles are introduced, and flavors are not conserved.



$$(m_{\tilde{l}}^2)_{ij} = (m_l m_l^\dagger)_{ij} + (\tilde{m}_l^2)_{ij} \quad (i,j = 1-3)$$

slepton mass matrix — lepton mass matrix — SUSY breaking to slepton masses

- SUSY flavor problem



$$Br(\mu \to e\gamma) \sim \frac{\alpha}{4\pi} \times \left(\frac{m_W}{m_{SUSY}}\right)^4 \sin^2\theta_{\tilde{e}\tilde{\mu}} \left(\frac{\Delta m_{\tilde{l}}^2}{m_{SUSY}^2}\right)^2$$

Proposals:
1) Universal scalar mass hypothesis $\Delta m_{\tilde{l}}^2 \ll m_{\tilde{l}}^2$
2) Alignment hypothesis: $\sin^2\theta_{\tilde{e}\tilde{\mu}} \ll 1$
3) Decoupling hypothesis: $m_{SUSY} \gg m_W$

cLFV studies unveil nature of the SUSY breaking and interaction beyond the SUSY SM.

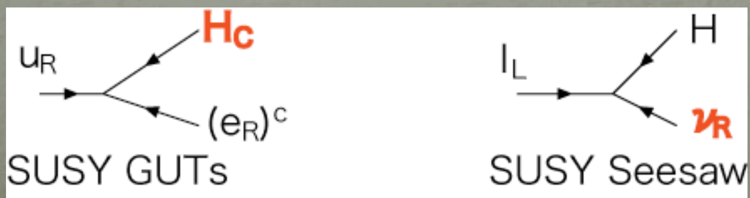
Universal scalar mass hypothesis

● The universal scalar mass hypothesis (USMH) is realized in many SUSY breaking. (ex, MSUGRA, GMSB, AMSB, etc)

● LFV interactions beyond the SUSY SM generate LFV mass terms for sleptons even under USMH.

(Hall, Kostelecky & Raby)

● SUSY GUTs and Seesaw models have LFV interactions and cLFVs are predicted. (Barbieri & Hall), (Borzumati & Masiero)



MSUGRA scenario

SUGRA generates SUSY breaking Terms at Planck scale.

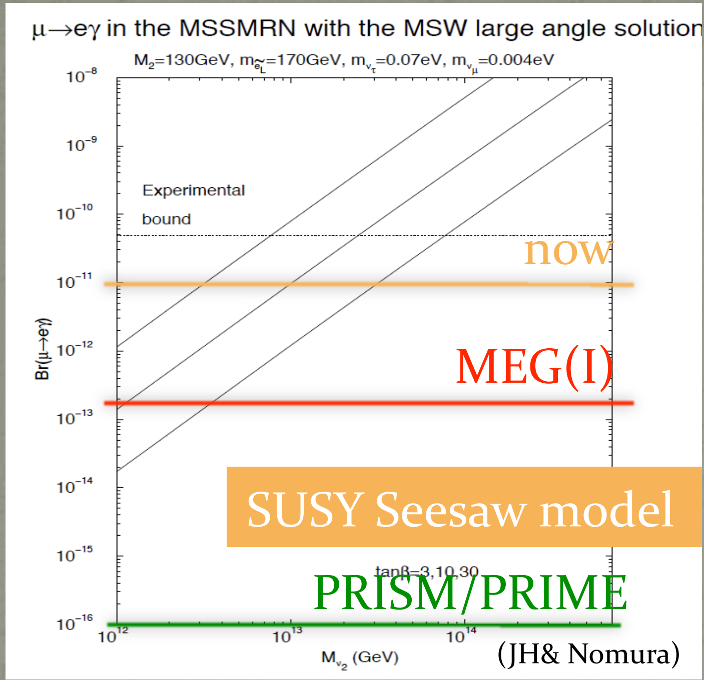
$$(m^2_{\tilde{l}})_{ij} = m^2_0 \delta_{ij}$$

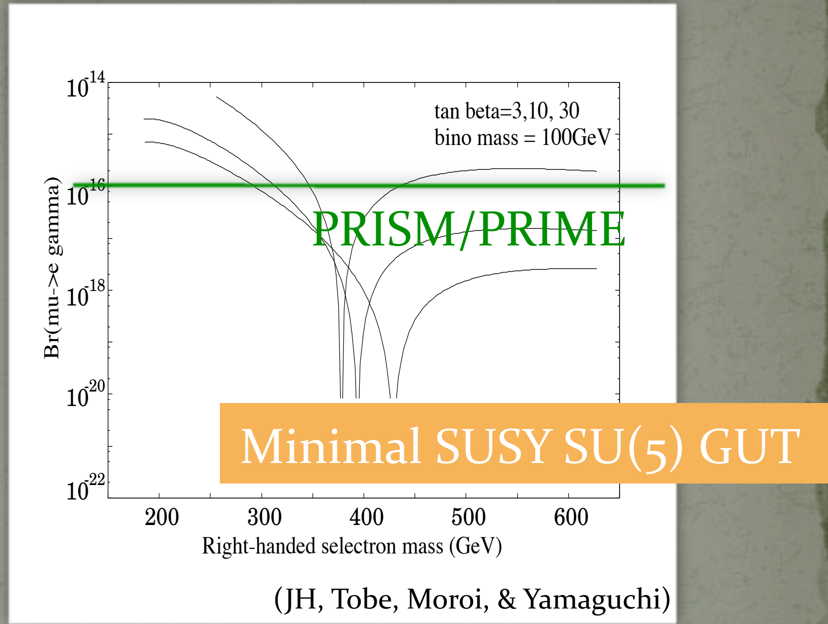
SUSY GUTs
Quark and lepton are unified.
SUSY Seesaw
Neutrino masses are generated.

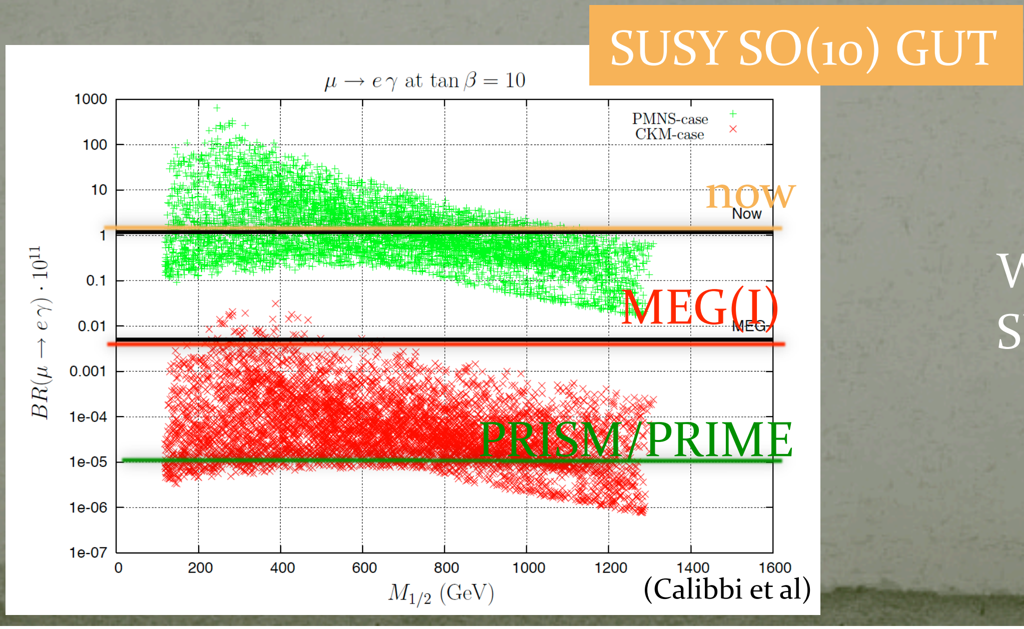
$$(m^2_{\tilde{l}})_{ij} = m^2_0 \delta_{ij} + \Delta(m^2_{\tilde{l}})_{ij}$$

SUSY SM
Charged LFV processes are predicted.

SUSY Seesaw and SUSY GUTs







We may probe physics beyond SUSY SM by studying cLFV.

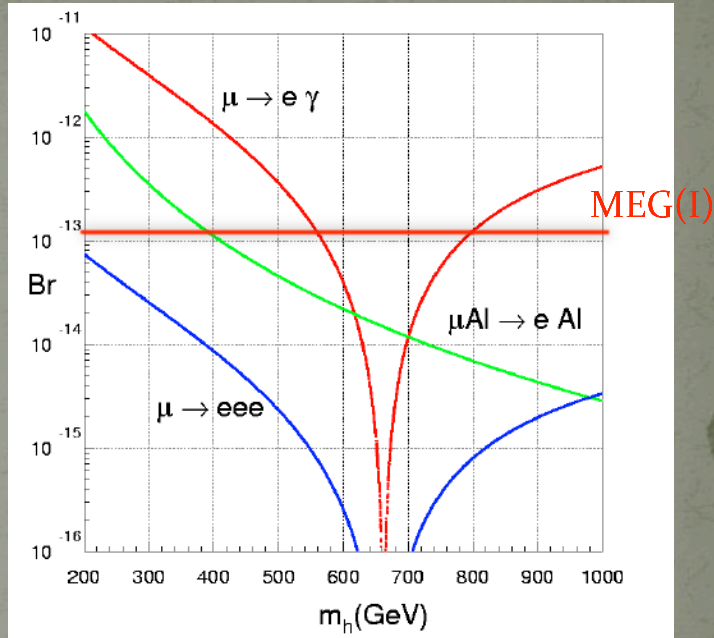
Higgs mediation in Decoupling hypothesis

- When SUSY particle masses are larger than O(1-10) TeV, the Higgs exchange dominates in cLFV processes since SUSY SM has two doublet Higgs bosons.

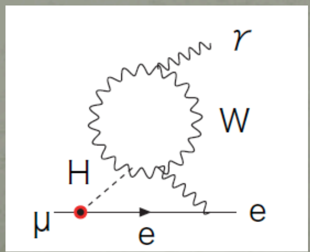
(Babu & Kolda)

$$-\mathcal{L}_Y = \bar{l}_{Ri} Y_{li} L_i H_1 + \bar{l}_{Ri} \Delta_{ij} L_j H_2 + h.c.$$

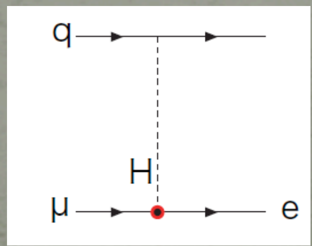
Tree One-loop

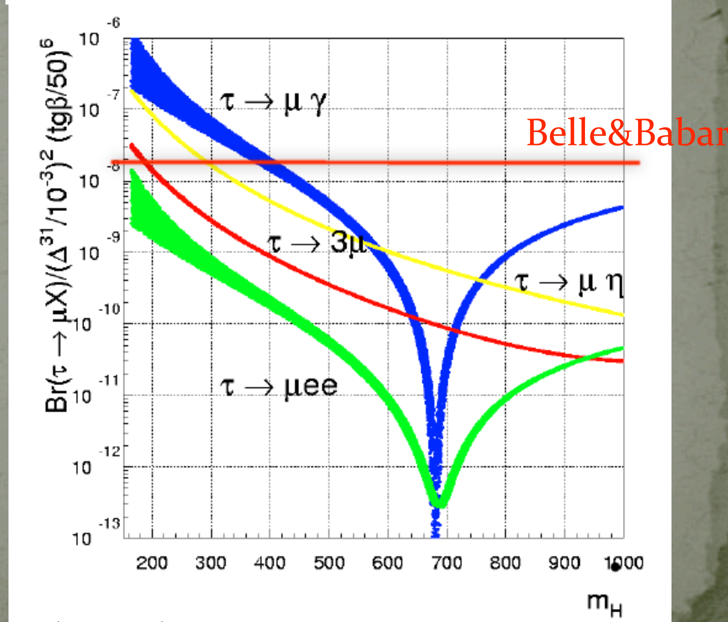


- $\mu \to e\gamma$ and $\tau \to \mu(e)\gamma$ are generated by Barr-Zee type two-loop diagrams, and they are competitive to or larger than other tree-level processes.



Barr-Zee





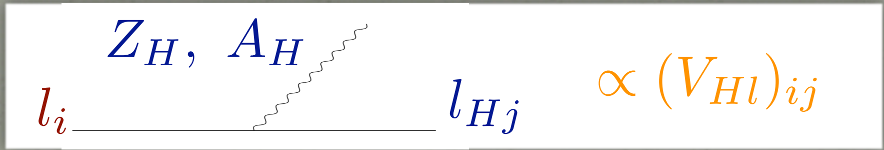
(Paradisi)

Non-SUSY BSMs at TeV scale

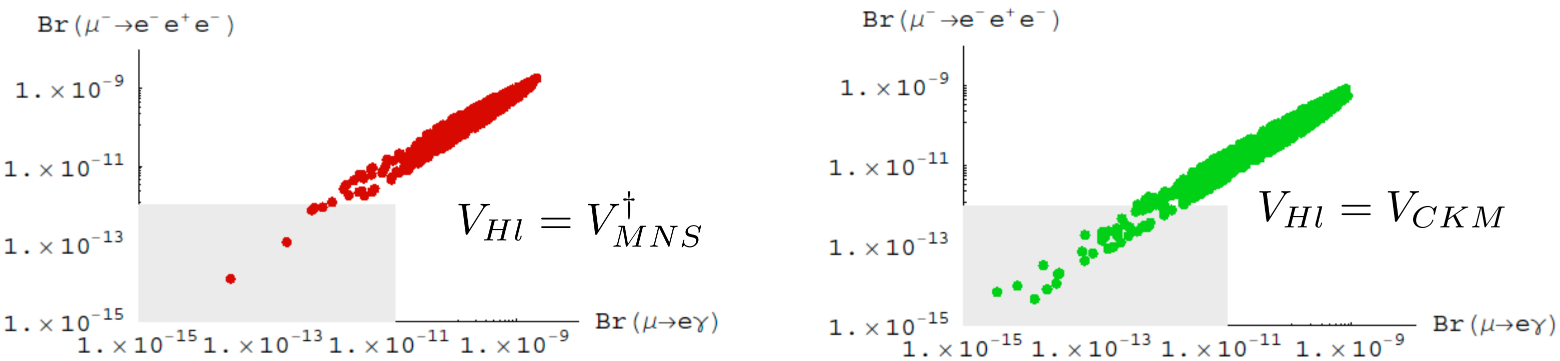
Little Higgs model with T parity

1) Higgs is a pseudo Nambu-Goldstone boson for symmetry breaking,
2) Quadratic div. to m_H is cancelled by heavy particles at 1-loop level.
3) T parity is introduced for EW precision tests.

T-odd SU(2) doublet mirror fermions have flavor-violating interactions.



cLFV processes are generated at 1-loop diagrams. $\mu \to e\gamma$ is accidentally suppressed by cancellation among diagrams.



$300\,\mathrm{GeV} \leq m^{\ell}_{Hi} \leq 1.5\,\mathrm{TeV}$

(Blanke et al)

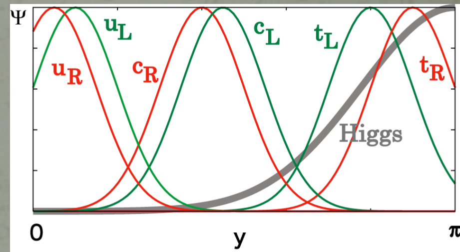
Non-SUSY BSMs at TeV scale (contd)

bulk SM in the Randall-Sundrum (RS) background

- RS background along 5th dimension solves hierarchy problem

$$ds^2 = e^{-2kr_c y}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 y^2 \quad (0 \le y \le \pi)$$

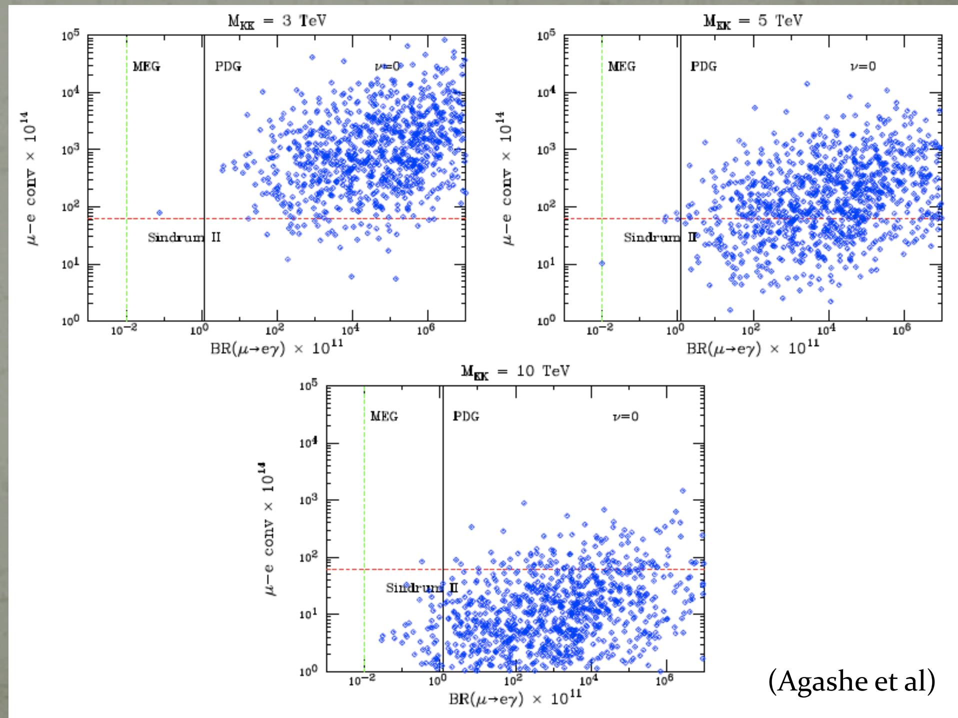
$$\Rightarrow \quad m_{\rm weak} \simeq e^{-2\pi k r_c} M_{pl}$$



- Fermion mass hierarchy is explained by O(1) parameters due to overlapping of wave functions when SM fields spread over 5th dim. space.

- Interactions of Kaluza-Klein (KK) gauge bosons with masses at TeV are flavor-violating, and cLFV processes are generated even at tree level.

- This model is constrained strongly from cLFVs.



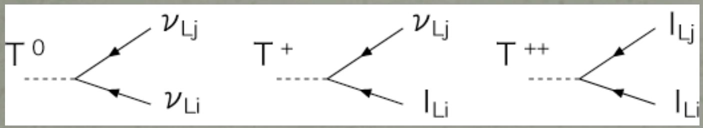
(Agashe et al)

Neutrino mass generation at TeV scale

It is believed that neutrino masses are generated at very high energy. However, when they come from TeV-scale physics, cLFVs are directly linked to them.

Triplet Higgs model (Type-II seesaw model)

- Neutrino masses are derived by $SU(2)_L$ triplet Higgs boson with mass at weak scale.



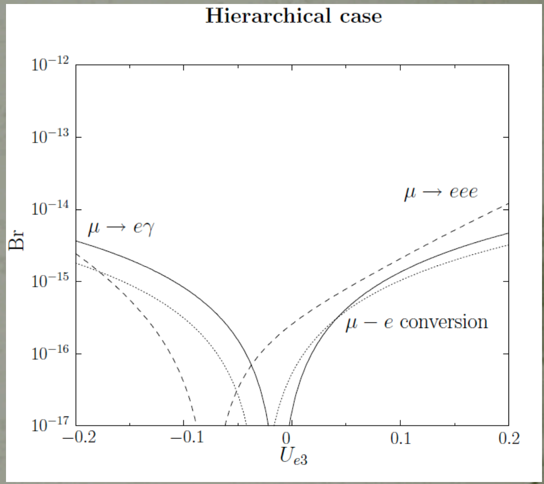
- $\mu \to 3e$ is generated at tree level while $\mu \to e\gamma$ and $\mu - e$ conversion are at one-loop level.

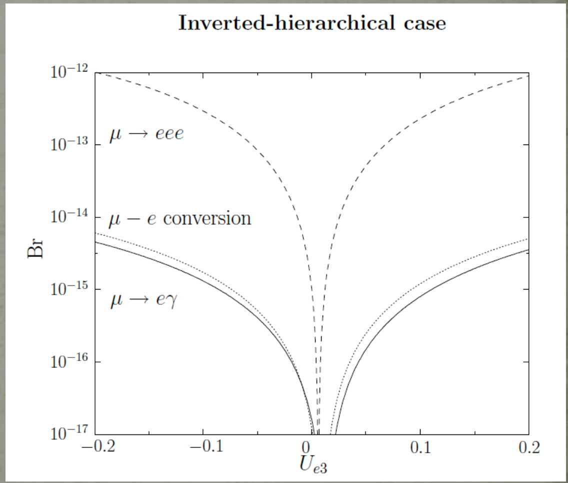
- cLFV processes are related to neutrino mass matrix.

$$\frac{Br(\tau \to \mu\gamma)}{Br(\mu \to e\gamma)} \simeq \left(\frac{(m_\nu^\dagger m_\nu)_{\tau\mu}}{(m_\nu^\dagger m_\nu)_{\mu e}} \right) \sim 300$$

Minimal flavor violation in lepton sector.

(Cirigliano, Grinstein, Isidori, & Wise)





(Kakizaki et al)

Correlations

cLFVs are indirect probes to new physics, then we need to take correlations among various processes to understand BSMs, source of flavor violation, and underlying flavor structure.

- Among cLFVs for common flavor transitions
- Between leptonic and hadronic FCNCs.
- ....

Among cLFVs for common flavor transitions

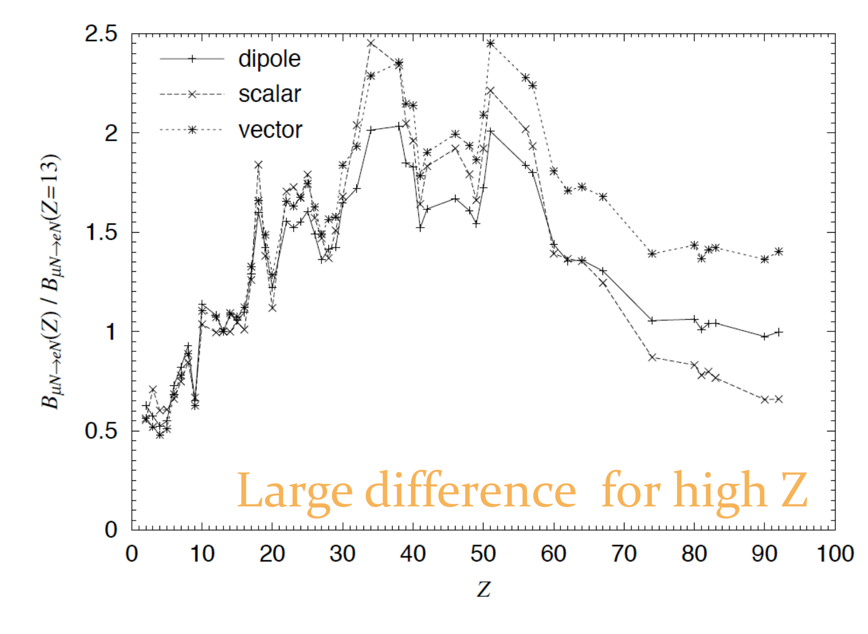
It is important to take correlations among cLFV processes in order to discriminate models with LFV. Pattern of correlations depends on models, and we have various LFV observables.

Ratios of branching ratios for three models

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.4\ldots2.5$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.4\ldots2.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.4\ldots2.3$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.3\ldots1.6$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.3\ldots1.6$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$1.3\ldots1.7$	~ 5	$0.3\ldots0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$1.2\ldots1.6$	~ 0.2	$5\ldots10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-2}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$

(Blanke et al)

Z dependence of μ–e conversion rate



(Kitano,Koike &Okada)

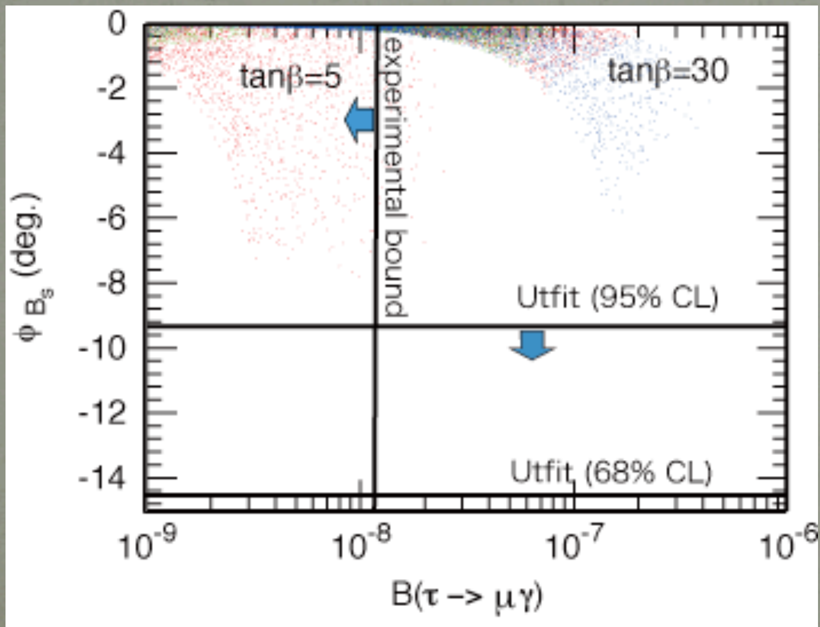
Between hadronnic and leptonic FCNCs

In GUTs, quarks and leptons are unified. cLFVs are correlated with hadronic FCNCs.

Ex, SUSY SU(5) GUT with right-handed neutrinos

$$\mathbf{10} : (u_L,\ d_L, (u_R)^c,\ (e_R)^c) \quad \mathbf{5}^\star : ((d_R)^c,\ e_L,\ \nu_L) \quad \mathbf{1} : (\nu_R)$$

Neutrino Yukawa affects $\tilde{d}_R$ mass matrix in addition to those of $\tilde{e}_L$ and $\tilde{\nu}_L$.



(JH & Shimizu)

Correlation between hadronic and leptonic transition from 3rd to 2nd generations induced by large neutrino angle.

Recently, UTfit group announces that CP phase in Bs mixing is more than 3-sigma deviated from the SM.

$$C_{B_s} e^{2i\phi_{B_s}} \equiv \frac{\langle B_s|H_{\rm eff}^{\rm full}|\bar{B}_s\rangle}{\langle B_s|H_{\rm eff}^{\rm SM}|\bar{B}_s\rangle}$$

Summary

- Charged lepton-flavor violation (cLFV) processes are accidentally suppressed by the GIM mechanism in the SM even after tiny neutrino masses are introduced. On the other hand, they are not necessarily automatic in the Beyond-Standard Models (BSMs). Studies of cLFVs probe BSMs, hidden flavor symmetries, and underlying flavor structures.

- Current bounds on μLFVs give constraints on physics even around O ($10^{2\text{-}3}$) TeV. In practical BSMs, cLFVs are suppressed by loop-factors or small flavor-mixing, or accidental cancellation. Thus, coming MEG experiment, and planed experiments, Mu2e, COMET and PRISM/PRIME, will cover interesting regions in various BSMs.

- cLFVs are pieces of puzzles in the SM and BSMs. Taking various correlations are useful to solve the puzzles.

Thanks !