On Charged-Lepton Flavor Violation and the Scale of New Physics

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Charged-Lepton Flavor Violation:

Key Probe of Physics Beyond the Standard Model!

- Sensitivity to very heavy new physics particles;
- Potential to elucidate origin of neutrino masses;
- Test of flavor structure of new physics at the weak scale (if any).

What Will Happen in the Near Future (my Optimistic View)

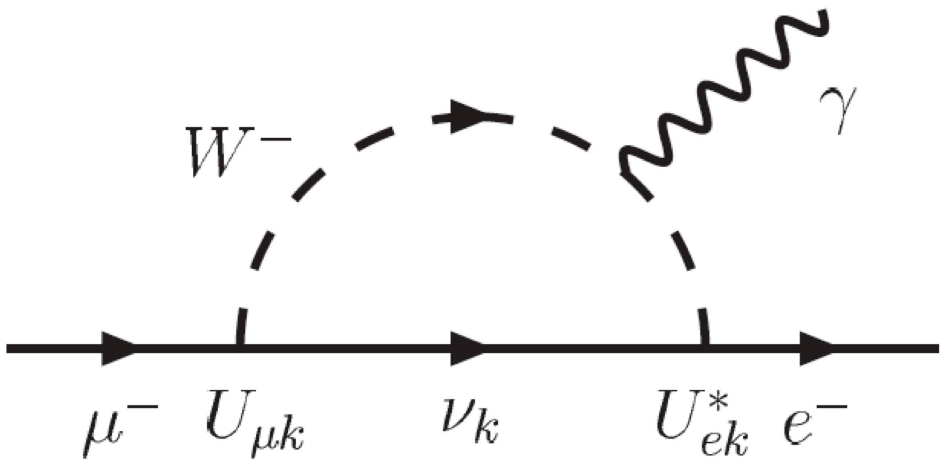
- MEG: $\mu \to e\gamma$ at 10^{-13}.
- $g-2$ measurement a factor of 3–4 more precise.
- Mu2e and COMET: $\mu \to e$-conversion at 10^{-16}.
- PSI: $\mu \to eee$ at 10^{-15}.
- SuperB: Rare τ processes at 10^{-10}.
- Project X-like: $\mu \to e$-conversion at 10^{-18} (or precision studies?).
- Project X-like: deeper probe of muon edm.
- Muon Beams/Rings: $\mu \to e$-conversion at 10^{-20}? Revisit rare muon decays ($\mu \to e\gamma$, $\mu \to eee$) with new idea?

One contribution known to be there: active neutrino loops (same as quark sector).

In the case of charged leptons, the **GIM suppression is very efficient**...

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

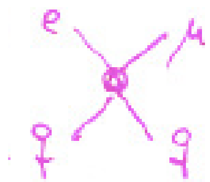
[$U_{\alpha i}$ are the elements of the leptonic mixing matrix,
$\Delta m^2_{1i}\equiv m^2_i-m^2_1$, $i=2,3$ are the neutrino mass-squared differences]

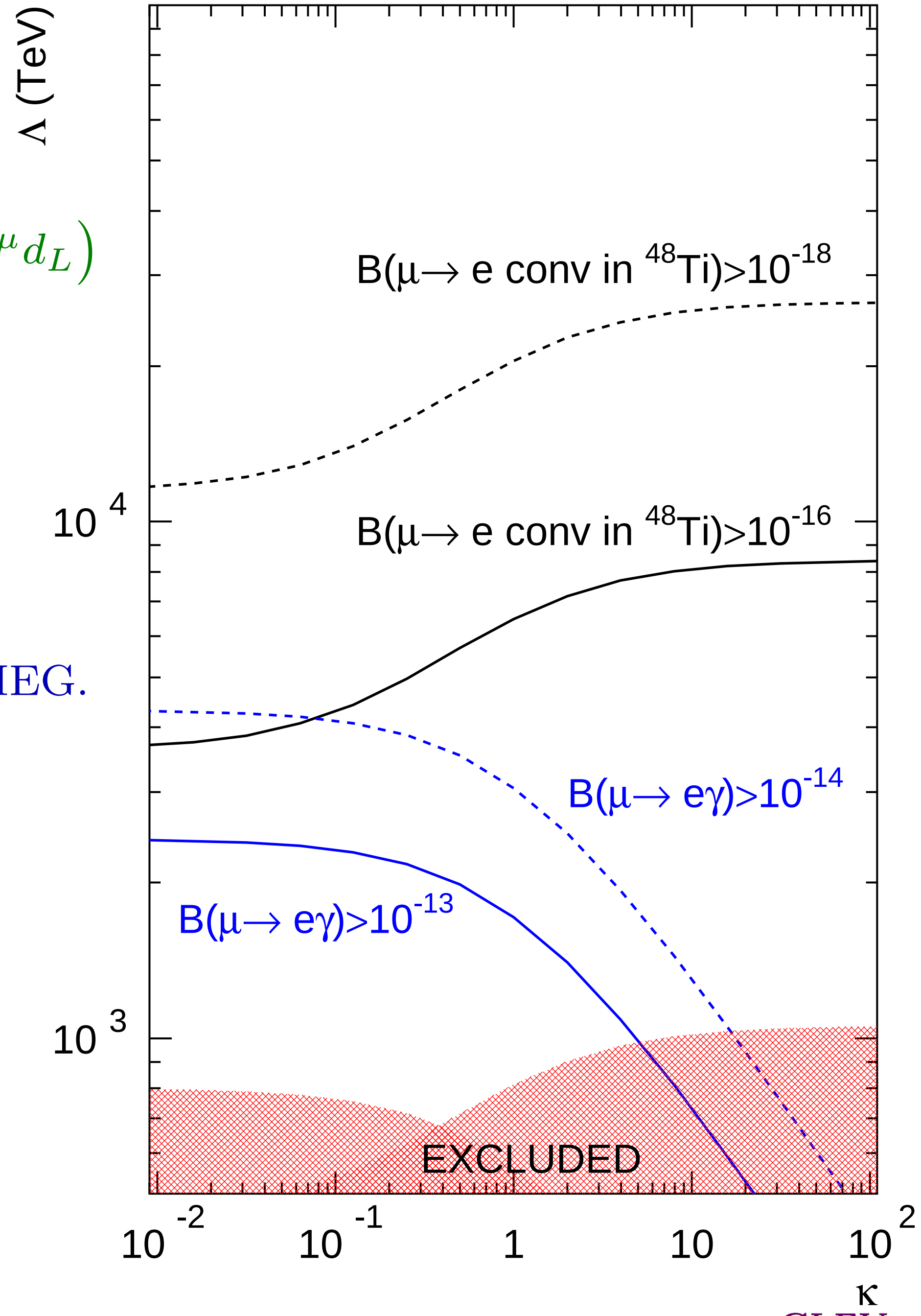


Model Independent Considerations

$$L_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} +$$
$$+\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

- $\mu \to e$-conv at 10^{-17} "guaranteed" deeper probe than $\mu \to e\gamma$ at 10^{-14}.
- We don't think we can do $\mu \to e\gamma$ better than 10^{-14}. $\mu \to e$-conv "only" way forward after MEG.
- If the LHC does not discover new states $\mu \to e$-conv among very few process that can access 1000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.

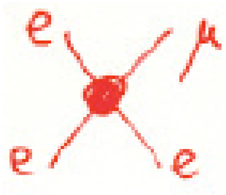


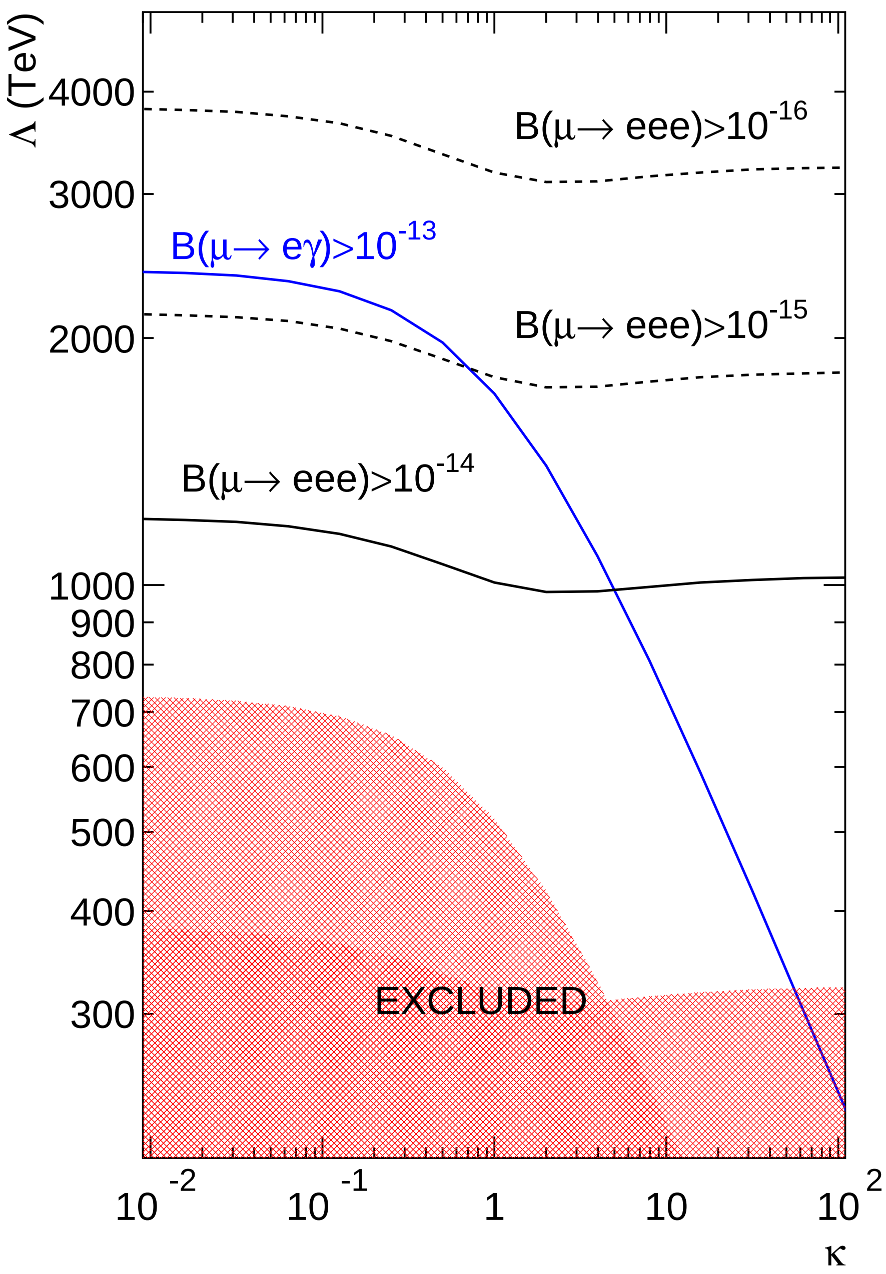


Other Example: $\mu \to e e^+ e^-$

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + $$
$$+ \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \bar{e}\gamma^\mu e$$

- $\mu \to eee$-conv at 10^{-16} “guaranteed” deeper probe than $\mu \to e\gamma$ at 10^{-14}.
- $\mu \to eee$ another way forward after MEG?
- If the LHC does not discover new states $\mu \to eee$ among very few process that can access 1,000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.





What does "Λ" mean?

This is clearly model dependent! However, some general issues are easy to identify…

- $\mu \to e\gamma$ always occurs at the loop level, and is suppressed by E&M coupling e. Also chiral suppression (potential for "$\tan\beta$" enhancement).

$$\frac{1}{\Lambda^2} \sim \frac{e}{16\pi^2}\frac{\tan\beta}{M^2_{\rm new}}$$

- $\mu \to eee$ and $\mu \to e$-conversion in nuclei can happen at the tree-level

$$\frac{1}{\Lambda^2} \sim \frac{y^2_{\rm new}}{M^2_{\rm new}}$$

SUSY with R-parity Violation, a Proxy for Lepto-Quarks and Other Beasts

Concretely, trilinear RPV:

$$\begin{aligned}\mathcal{L} &= \lambda_{ijk}\left(\bar{\nu}^c_{Li}e_{Lj}\tilde{e}^*_{Rk} + \bar{e}_{Rk}\nu_{Li}\tilde{e}_{Lj} + \bar{e}_{Rk}e_{Lj}\tilde{\nu}_{Li}\right) \\ &+ \lambda'_{ijk}V^{j\alpha}_{KM}\left(\bar{\nu}^c_{Li}d_{L\alpha}\tilde{d}^*_{Rk} + \bar{d}_{Rk}\nu_{Li}\tilde{d}_{L\alpha} + \bar{d}_{Rk}d_{L\alpha}\tilde{\nu}_{Li}\right) \\ &- \lambda'_{ijk}\left(\bar{u}^c_j e_{Li}\tilde{d}^*_{Rk} + \bar{d}_{Rk}e_{Li}\tilde{u}_{Lj} + \bar{d}_{Rk}u_{Lj}\tilde{e}_{Li}\right) + \text{h.c.},\end{aligned}$$

The presence of different combinations of these terms leads to very distinct patterns for CLFV. Proves to be an excellent laboratory for probing all different possibilities. [AdG, Lola, Tobe, hep-ph/0008085]

Incidently, if SUSY breaking happens at a very high scale, neutrino masses and CLFV among few "handles" one can still grasp for.

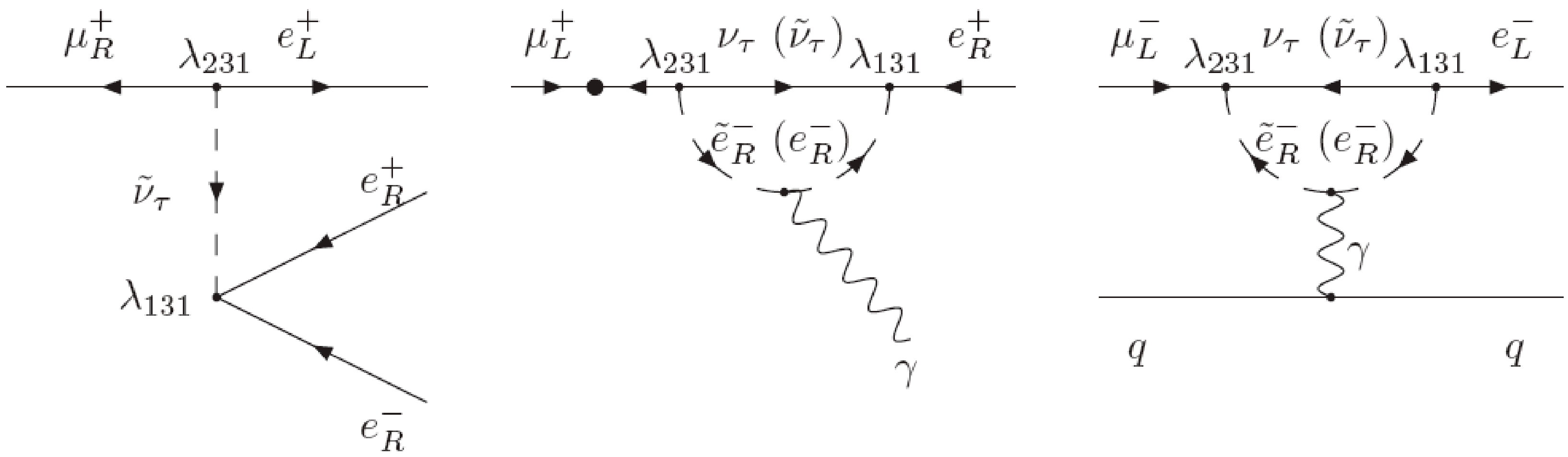


Figure 1: *Lowest order Feynman diagrams for lepton flavour violating processes induced by $\lambda_{131}\lambda_{231}$ couplings (see Eq. (2.1)).*

$$\frac{\mathrm{Br}(\mu^+\to e^+\gamma)}{\mathrm{Br}(\mu^+\to e^+e^-e^+)} = \frac{4\times 10^{-4}\left(1-\frac{m^2_{\tilde{\nu}_\tau}}{2m^2_{\tilde{e}_R}}\right)^2}{\beta} \simeq 1\times 10^{-4} \qquad (\beta\sim 1)$$

$$\frac{\mathrm{R}(\mu^-\to e^- \text{ in Ti (Al)})}{\mathrm{Br}(\mu^+\to e^+e^-e^+)} = \frac{2\ (1)\times 10^{-5}}{\beta}\left(\frac{5}{6}+\frac{m^2_{\tilde{\nu}_\tau}}{12m^2_{\tilde{e}_R}}+\log\frac{m_e^2}{m^2_{\tilde{\nu}_\tau}}+\delta\right)^2 \simeq 2\ (1)\times 10^{-3},$$

$\mu^+\to e^+e^-e^+$ most promising channel!

[AdG, Lola, Tobe, hep-ph/0008085]

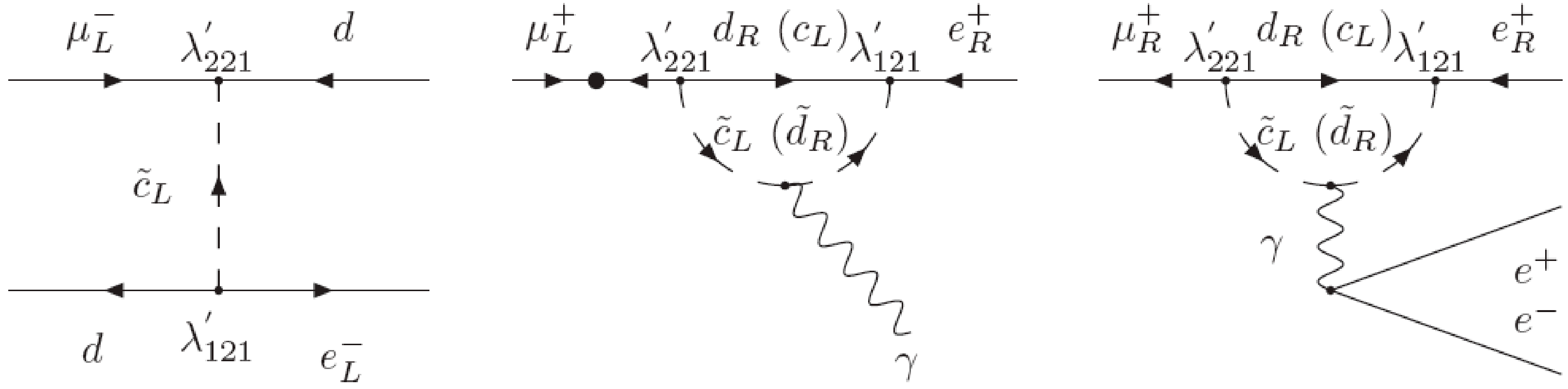


Figure 4: *Lowest order Feynman diagrams of lepton flavour violating processes induced by $f'_{121}f'_{221}$ couplings (see Eq. (2.1)).*

$$\frac{\mathrm{Br}(\mu^+\to e^+\gamma)}{\mathrm{Br}(\mu^+\to e^+e^-e^+)} = 1.1$$

$$(m_{\tilde{d}_R} = m_{\tilde{c}_L} = 300\ \mathrm{GeV})$$

$$\boxed{\frac{\mathrm{R}(\mu^-\to e^-\ \text{ in Ti (Al)})}{\mathrm{Br}(\mu^+\to e^+e^-e^+)} = 2\ (1)\times 10^5}$$

$\mu - e$-conversion "only hope"!

[AdG, Lola, Tobe, hep-ph/0008085]

Type-II Seesaw: SM plus $SU(2)$ Triplet Higgs, $Y_T = 1$

$$\mathcal{L} \in \frac{\lambda_{\alpha\beta}}{2} L^\alpha L^\beta T.$$

Neutrino Majorana masses if T develops a vev ...

$$m_{\alpha\beta} = \lambda_{\alpha\beta} v_T$$

$\mu \to e\gamma$, $\mu \to e$-conversion at the loop-level. However, $\mu \to eee$ at the tree level (note direct connection to neutrino mass-matrix flavor sctructure)...

$$\frac{1}{\Lambda^2} = \frac{m_{ee} m_{\mu e}}{v_T^2 M_T^2}$$

Key issue: are neutrino masses small because λ are small or because v_T is small (or both)? EWPD already push v_T below ~ 1 GeV...

What is This Really Good For?

While specific models provide estimates for the rates for CLFV processes, the observation of one specific CLFV process cannot determine the underlying physics mechanism (this is always true when all you measure is the coefficient of an effective operator).

Real strength lies in combinations of different measurements, including:

- kinematical observables (e.g. angular distributions in $\mu \to eee$);
- other CLFV channels;
- neutrino oscillations;
- measurements of $g-2$ and EDMs;
- collider searches for new, heavy states;
- etc.

Model Independent Comparison Between $g-2$ and CLFV:

The dipole effective operators that mediate $\mu \to e\gamma$ and contribute to a_μ are virtually the same:

$$\frac{m_\mu}{\Lambda^2}\bar{\mu}\sigma^{\mu\nu}\mu F_{\mu\nu} \qquad \times \qquad \theta_{e\mu}\frac{m_\mu}{\Lambda^2}\bar{\mu}\sigma^{\mu\nu}eF_{\mu\nu}$$

$\theta_{e\mu}$ measures how much flavor is violated. $\theta_{e\mu}=1$ in a flavor indifferent theory, $\theta_{e\mu}=0$ in a theory where indiviadual lepton flavor number is exactly conserved.

If $\theta_{e\mu}\sim 1$, $\mu\to e\gamma$ is a much more stringent probe of Λ.

On the other hand, if the current discrepancy in a_μ is due to new physics, $\theta_{e\mu}\ll 1$ ($\theta_{e\mu}<10^{-4}$). [Hisano, Tobe, hep-ph/0102315]

e.g., in SUSY models, $Br(\mu\to e\gamma)\simeq 3\times 10^{-5}\left(\frac{10^{-9}}{\delta a_\mu}\right)\left(\frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\tilde{m}^2}\right)^2$

Comparison restricted to dipole operator. If four-fermion operators are relevant, they will "only" enhance rate for CLFV with respect to expectations from $g-2$.

What we can learn from CLFV and other searches for new physics at the TeV scale (a_μ and Colliders):

$g-2$	CLFV	What Does it Mean?
YES	YES	New Physics at the TeV Scale; Some Flavor Violation
YES	NO	New Physics at the TeV Scale; Tiny Flavor Violation
NO	YES	New Physics Above TeV Scale; Some Flavor Violation – How Large?
NO	NO	No New Physics at the TeV Scale; CLFV only way forward?

Colliders	CLFV	What Does it Mean?
YES	YES	New Physics at the TeV Scale; Info on Flavor Sector!
YES	NO	New Physics at the TeV Scale; New Physics Very Flavor Blind. Why?
NO	YES	New Physics “Leptonic” or Above TeV Scale; Which one?
NO	NO	No New Physics at the TeV Scale; CLFV only way forward?