Charged Lepton Flavor Violation in a Class of Radiative Neutrino Mass Generation Models

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Motivation

- Both the Origin and Smallness of the Neutrino mass and the Dark Matter of the universe haven't been explained conclusively by the Physics Beyond Standard Model (BSM).
- A well-motivated approach is to identify any interplay between the Dark matter and neutrino that is responsible for neutrino's small non-zero mass.
- This leads to a Radiative Neutrino Mass Generation Model (RνMass Model) where the dark matter particles enter into the loop diagrams that give the neutrino its mass.
- A nice feature of Rν Mass model is that its particle content is accessible to currently operating LHC or future colliders.
- In this talk, we will address the viability of such RνMass model: 3-loop Krauss-Nasri-Trodden (KNT) model in the light of **bounds** on Charged Lepton Flavor Violation (LFV). arXiv:hep-ph/0210389

Rν Mass Model: The minimal KNT Approach

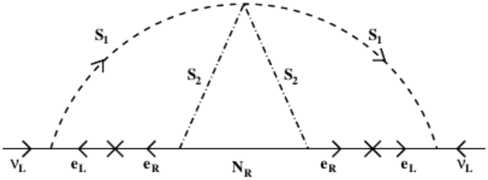


Figure : Neutrino mass generation in the minimal KNT model at 3-loop.

In addition to the Standard Model (SM) particle content, the KNT model contains,

- Two single charged scalars, S_1^+, S_2^+.
- Three right handed fermion singlets, N_{R_i} under the SM Gauge Group.
- Here $\{S_2^+, N_{R_i}\}$ are charged under Z_2. Because of this Z_2 symmetry, the lightest fermion singlet, N_{R_1} acts as the DM candidate.

The Generalized KNT model with Large Electroweak Multiplets

- Subsequently it was found that, the minimal field content of 3-loop KNT model can be generalized with larger electroweak multiplets,

$$S_2^+ \to \mathbf{\Phi} = \left(\phi^{(n+1)}, ..., \phi^+, \phi^0, \phi'^-, ..., \phi'^{(-n+1)}\right)^T_{Y=1}$$

$$N_{R_i} \to \mathbf{F_i} = \left(F_i^{(n)}, ..., F_i^+, F_i^0, F_i^-, ..., F_i^{(-n)}\right)^T_{Y=0}$$

arXiv:1404.2696; 1404.5917; 1504.05755

- There is no symmetry to forbid replacing the minimal field content of the KNT model with larger electroweak (EW) multiplets.
- This replacement with larger EW multiplets leave the topology of the neutrino mass generation loop diagram invariant.
- Advantage of large electroweak multiplet: Appearance of accidental symmetry which can forbid the Dirac neutrino mass term ($n \geq 2$) and automatically stabilize the DM ($n \geq 3$). No Z_2 symmetry is needed.
- So we focus on singlet ($n = 0$), triplet ($n = 1$), 5-plet ($n = 2$) and 7-plet ($n = 3$) systematically to determine their viabilities.

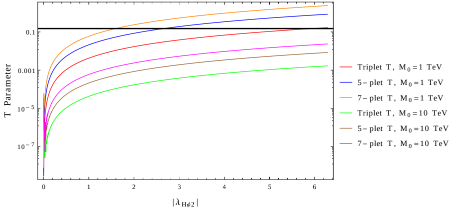
Charged Lepton Flavor Violation

- Lepton flavor violation is ubiquitous among the neutral leptons i.e. neutrino oscillation.
- What about the charged lepton flavor violation?
- In the SM, with massive neutrino of $m_\nu \sim O(0.1\,\text{eV})$ and Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix, U_{PMNS}, the branching ratio of $\mu \to e\gamma$ turns out to be about 10^{-49}.
- But many BSM scenario, especially the new physics related to the generation of the neutrino mass can lead to unsuppressed charged LFV processes.
- Therefore, one can also expect large charged LFV in Rν Mass model like the KNT model.

The Lagrangian of the generalized KNT model contains

$$\mathcal{L} \supset \mathcal{L}_{SM} + i\overline{\mathbf{F}}_i \not{D} \mathbf{F}_i + (D_\mu \mathbf{\Phi})^\dagger (D^\mu \mathbf{\Phi}) + (D_\mu S_1)^\dagger (D^\mu S_1) - V(H, \mathbf{\Phi}, S_1) \\ - \frac{M_{F_i}}{2} \overline{\mathbf{F}^c_i} \mathbf{F}_i + f_{\alpha\beta} \overline{l^c_{L_\alpha}} l_{L_\beta} . S_1^+ + g_{i\alpha} \overline{\mathbf{F}}_i . \mathbf{\Phi} . e_{R_\alpha} + h.c$$

- In the limit, $M_F \gg M_W$, the mass splitting between the $F^{(Q)}$ and $F^{(Q')}$ is, $M_Q - M_{Q'} \sim (Q^2 - {Q'}^2)\Delta$ where, $\Delta \equiv \alpha_W \sin^2(\theta_w/2) M_W \sim 166$ MeV. hep-ph/0512090
- For, $M_{F_i} \sim 10$ TeV, $\Delta m^2_{F_i}/M^2_{F_i} \sim 10^{-4}$.
- $V \supset \lambda_{H\phi_2} (\mathbf{\Phi}^* . H).(H^* . \mathbf{\Phi})$ gives the mass splittings in the scalar multiplet.
- For, $m_\phi \sim 10$ TeV and $\lambda_{H\phi_2} \sim 2\pi$, Maximum allowed splitting, $\Delta m^2_{ij}/m^2_\phi \sim 10^{-3}$.



So we consider both fermion and scalar components almost degenerate. It's the 'near-degenerate limit' of the KNT model.

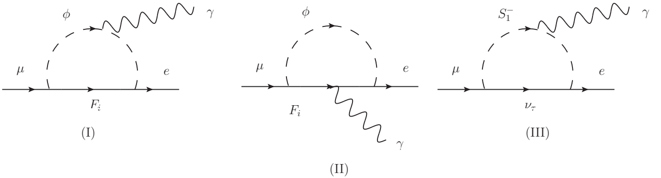
Limits on Charged LFV Processes

LFV Process	Present Bound	Future Sensitivity
$\mu \to e\gamma$	4.2×10^{-13} (MEG)	5.4×10^{-14} (MEGII)
$\mu \to 3e$	10^{-12} (SINDRUM)	10^{-16} (Mu3e)
$\mu, Au \to e, Au$	7×10^{-13} (SINDRUM II)	6.7×10^{-17}
$\mu, Ti \to e, Ti$	4.3×10^{-12} (SINDRUM II)	(Mu2e)

MEG:arXiv:1605.05081, MEGII:arXiv:1705.10224, SINDRUM: Nucl. Phys. B **299** (1988) 1., Mu3e:Nucl. Part. Phys. Proc. **287-288** (2017) 169., SINDRUM II: Eur. Phys. J. C **47** (2006) 337 & Phys. Lett. B **317** (1993) 631., Mu2e: Nuovo Cim. C **40** (2017) no.1, 48.

As the $\mu \to e\gamma$, $\mu \to ee\bar{e}$ and $\mu - e$ conversion in nuclei have the most sensitive limits, we have focused on them in this work.

$\mu \to e\gamma$



- The scalar-fermion pair $\{\phi^{(-q)}, F_i^{(q-1)}\}$ where, $q = -n+1, ...n+1$ give the dipole contribution to $\mu \to e\gamma$.
- $\{S_1^+, \nu_\tau\}$ pair also contributes to the LFV process.

$$A_D^{(1)} = \sum_{i=1}^{3} \sum_{\phi} \frac{g_{ei}^* g_{i\mu} q_\phi}{32\pi^2} \frac{1}{m_\phi^2} F_1(x_{i\phi}^q), \quad A_D^{(2)} = -\sum_{i=1}^{3} \sum_{F_i} \frac{g_{ei}^* g_{i\mu} q_{F_i}}{32\pi^2} \frac{1}{m_\phi^2} F_2(x_{i\phi}^q), \quad A_D^{(3)} = \frac{f_{e\tau}^* f_{\tau\mu}}{192\pi^2} \frac{1}{m_S^2}$$

where, $x_{i\phi}^q = m^2_{F_i^{(q-1)}} / m^2_{\phi(-q)}$

$$\mathbf{\Phi} = \left(..., \phi^{++++}, \phi^{+++}, \phi^{++}, \phi^{+}, \phi^{0}, \phi^{'-}, \phi^{''--}, ...\right)^T$$

$$\mathbf{F_i} = \left(..., F_i^{+++}, F_i^{++}, F_i^{+}, F_i^{0}, F_i^{-}, F_i^{--}, F_i^{---}, ...\right)^T$$

- But there are cancellations in $A_D^{(2)}$ because degenerate fermion components with opposite electric charge have the photon line attached to it. The sum over all fermion components, thus, renders $A_D^{(2)} \sim 0$.
- Also similar cancellations take place in $A_D^{(1)}$ when scalar components of opposite charge have the photon line attached to it.
- So the non-negligible contributions come from,
  - triplet: (ϕ^{--}, F_i^{+}) and (ϕ^{-}, F_i^{0}) pairs.
  - 5-plet: (ϕ^{---}, F_i^{++}) and (ϕ^{--}, F_i^{+}) pairs.
  - 7-plet: (ϕ^{----}, F_i^{+++}) and (ϕ^{---}, F_i^{++}) pairs.

$\mu \to ee\bar{e}$: γ-penguin

The process, $\mu \to ee\bar{e}$ receives contributions from,

- γ-penguin diagrams
- Z-penguin diagrams
- Box diagrams

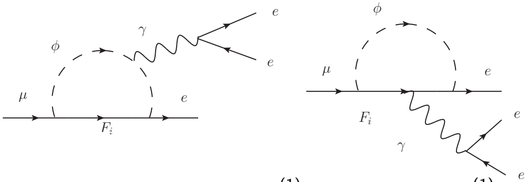


Figure : γ-penguin diagrams giving dipole $A_D^{(1)}$ and non-dipole $A_{ND}^{(1)}$ contributions (left fig). And similarly, $A_D^{(2)}$ and $A_{ND}^{(2)}$, respectively (right fig).

- Again the cancellations are at work and makes $A_{ND}^{(2)} \sim 0$ along with $A_D^{(2)} \sim 0$.
- Same pairs of (ϕ, F_i) that give non-zero contributions to $A_D^{(1)}$ also provide non-zero $A_{ND}^{(1)}$.

$\mu \to ee\bar{e}$: Z-penguin

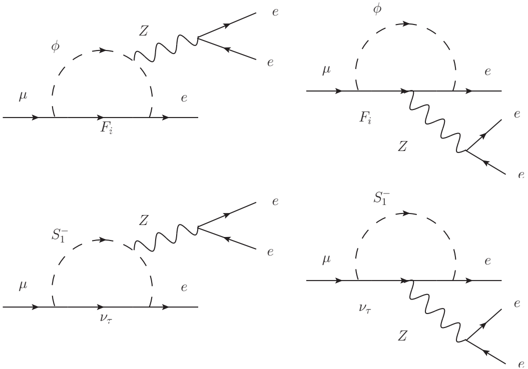


Figure : Z-penguin diagrams giving $F_Z^{(1)}$ (upper panel) and $F_Z^{(2)}$ (lower panel) contributions respectively.

triplet: $F_Z^{(1)}(\phi^{--}, F_i^+) = -F_Z^{(1)}(\phi^0, F_i^-)$. So the only non-zero contribution is $F_Z^{(1)}(\phi^-, F_i^0)$. $F_Z^{(2)}$ is also zero.

$$\text{5-plet}: \begin{cases} F_Z^{(1)}(\phi^{--}, F_i^+) & = -F_Z^{(1)}(\phi^0, F_i^-) \\ F_Z^{(1)}(\phi^{--}, F_i^+) & = -F_Z^{(1)}(\phi^0, F_i^-) \end{cases} \qquad \text{7-plet}: \begin{cases} F_Z^{(1)}(\phi^{----}, F_i^{+++}) & = -F_Z^{(1)}(\phi''^{++}, F_i^{---}) \\ F_Z^{(1)}(\phi^{---}, F_i^{++}) & = -F_Z^{(1)}(\phi'^{+}, F_i^{--}) \\ F_Z^{(1)}(\phi^{--}, F_i^{+}) & = -F_Z^{(1)}(\phi^0, F_i^-) \end{cases}$$

$\mu \to e e \bar{e}$: Box diagrams

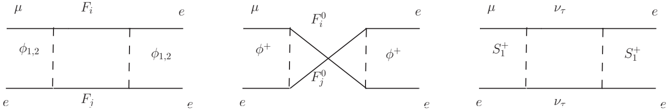


Figure : One loop box topologies associated to Feynman diagrams contributing to $\mu \to e e \bar{e}$.

- The increase of the multiplet size leads to the increase of box diagrams.
- Unlike the case of cancellations among different γ and Z-penguin diagrams, all box diagrams add up coherently.
- Therefore, one can expect dominant contribution of box diagrams in $\mu \to e e \bar{e}$ compared to the penguin diagrams.

$\mu - e$ Conversion in Nuclei

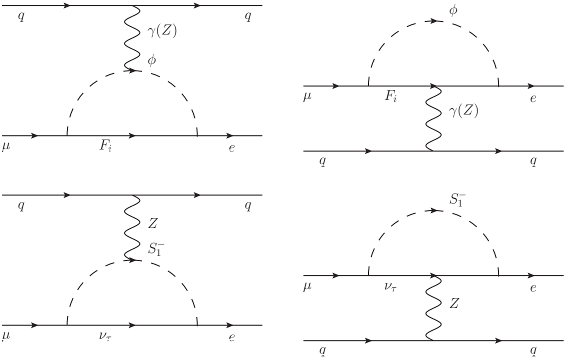


Figure : $\mu - e$ conversion only involves γ and Z-penguin diagrams.

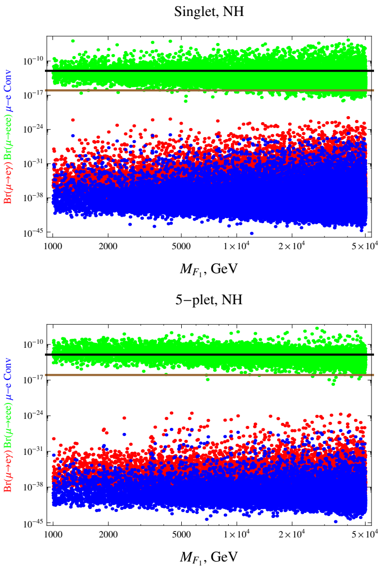
- No box diagram for the case of $\mu - e$ conversion in nuclei.
- γ-penguin leads to an effective coupling with the quark which is proportional to $(A_{ND} - A_D)/G_F$. Expected to be more suppressed than $\mu \to ee\bar{e}$.

Our Parameter Space

The relevant parameter space of the model in the near-degenerate limit consists of $\{M_{F_{1,2,3}}, m_\phi, m_S, f_{\alpha\beta}, g_{i\alpha}, \lambda_S\}$

- $M_{F_1} \in (1, 50)$ TeV; F_1^0 as a Dark Matter Candidate. So taken to be lightest to avoid decays like $F_1^0 \to \phi^+ e_R^-$ etc.
- $M_{F_{2,3}} \in M_{F_1} + (1, 10)$ TeV; We are considering Non-degenerate Fermion mass, $M_{F_1} < M_{F_{2,3}}$.
- $m_\phi \in M_{F_1} + (10, 100)$ TeV; Always to have $M_{F_1} < m_\phi$.
- $m_S \in (500\,\text{GeV}, 50\,\text{TeV})$; S_1^+ can be light as it doesn't enter into DM sector. Sensitivity study of $e^+e^- \to S_1^+ S_1^- \to l_\alpha^+ l_\beta^- + E_{\text{miss}}$ in ILC-like collider with $\sqrt{s} = 1$ TeV puts $m_S \gtrsim 240$ GeV. arXiv:1403.5694
- $\lambda_S \in (0.001, 0.1)$; Relevant for neutrino mass matrix.
- The yukawa couplings, $f_{\alpha\beta}$ and $g_{i\alpha}$ are chosen numerically so that they satisfy the low energy neutrino constraints.

Charged Lepton Flavor Violating Rates in KNT



Relative Contributions to Charged LFV Processes

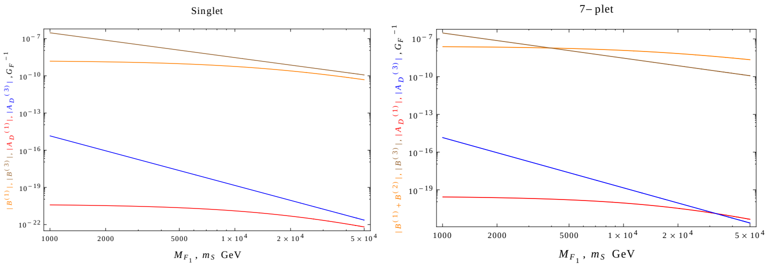


Figure : (Left) Relative comparison among dipole contributions, $A_D^{(1)}$ and $A_D^{(3)}$ and box contributions, $B^{(1)}$ and $B^{(3)}$ in G_F^{-1} unit for the singlet case. Here we can see that, box contributions are larger that dipole contributions. (Right) Similar comparison is made for the 7-plet case. As A_{ND} behaves similarly as A_D and also F_Z is comparatively smaller than A_D and B, we have not included them in the figure.

Conclusion

- The cancellations among several one-loop photonic dipole term, photonic non-dipole term and Z-penguin terms make the $\mu \to e\gamma$ and $\mu - e$ conversion in Au and Ti rates highly suppressed compared to $\mu \to ee\bar{e}$.
- Large rate of $\mu \to ee\bar{e}$ is due to the coherent addition of one-loop box diagrams where no cancellations take place.
- For $M_{F_1} = 1 - 50$ TeV mass range, the region of viable parameter space set is already excluded by the limit from SINDRUM and future Mu3e will exclude almost all of the parameter space.
- The pattern of LFV rates $Br(\mu \to ee\bar{e}) \gg Br(\mu \to e\gamma)$ & $\mu - e$ conv will point out to the Generalized KNT model.
- A possibe extension of this study will the looking into $\tau \to \mu\gamma$, $e\gamma$, $\tau \to 3e$ and $\tau \to 3\mu$ to understand more about flavor structure of the model.

Thank you very much for your attention.

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The Neutrino Mass Matrix is given by,

$$(M_\nu)_{\alpha\beta} = \frac{c\lambda_S}{(4\pi^2)^3}\frac{m_\gamma m_\delta}{m_\phi} f_{\alpha\gamma} f_{\beta\delta} g^*_{\gamma i} g^*_{\delta i} F\left(\frac{M^2_{F_i}}{m^2_\phi}, \frac{m^2_S}{m^2_\phi}\right)$$

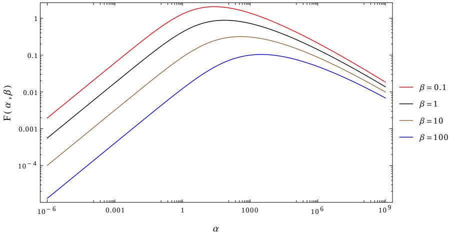

Figure : $F(\alpha,\beta)$ with $\alpha = M^2_{F_i}/m^2_\phi$ and $\beta = m^2_S/m^2_\phi$.

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The branching ratio for $\mu \to e\gamma$, normalized by $\mathrm{Br}(\mu \to e\overline{\nu_e}\nu_\mu)$, is

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3(4\pi)^3\alpha_{em}}{4G_F^2}\left|A_D\right|^2 \mathrm{Br}(\mu \to e\nu_\mu\overline{\nu_e})$$

where

$$A_D = A_D^{(1)} + A_D^{(2)} + A_D^{(3)}$$

where

$$A_D^{(1)} = \sum_{i=1}^{3}\sum_{\phi}\frac{g_{ei}^* g_{i\mu} q_\phi}{32\pi^2}\frac{1}{m_\phi^2}F_1(x_{i\phi}^q)$$

$$A_D^{(2)} = -\sum_{i=1}^{3}\sum_{F_i}\frac{g_{ei}^* g_{i\mu} q_{F_i}}{32\pi^2}\frac{1}{m_\phi^2}F_2(x_{i\phi}^q)$$

$$A_D^{(3)} = \frac{f_{e\tau}^* f_{\tau\mu}}{192\pi^2}\frac{1}{m_S^2}$$

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$$
\begin{aligned}
\mathrm{Br}(\mu \to ee\bar{e}) = \frac{3(4\pi)^2\alpha_{em}^2}{8G_F^2} & \left[|A_{ND}|^2 + |A_D|^2 \left(\frac{16}{3}\ln\frac{m_\mu}{m_e} - \frac{22}{3} \right) + \frac{1}{6}|B|^2 \right. \\
& \left. + \frac{1}{3}(2|F_Z^L|^2 + |F_Z^R|^2) + \left(-2A_{ND}A_D^* + \frac{1}{3}A_{ND}B^* - \frac{2}{3}A_D B^* + \mathrm{h.c} \right) \right] \\
& \times \mathrm{Br}(\mu \to e\overline{\nu_e}\nu_\mu)
\end{aligned}
$$

F_Z^L and F_Z^R are given as

$$
F_Z^L = \frac{F_Z g_L^l}{g^2 m_Z^2 \sin^2\theta_W} \quad , \quad F_Z^R = \frac{F_Z g_R^l}{g^2 m_Z^2 \sin^2\theta_W}
$$

$$
A_{ND}^{(1)} = \sum_{i=1}^{3}\sum_{\phi} \frac{g_{ei}^* g_{i\mu} q_\phi}{32\pi^2} \frac{1}{m_\phi^2} G_1(x_{i\phi}^q)
$$

$$
A_{ND}^{(2)} = -\sum_{i=1}^{3}\sum_{F_i} \frac{g_{ei}^* g_{i\mu} q_{F_i}}{32\pi^2} \frac{1}{m_\phi^2} G_2(x_{i\phi}^q)
$$

$$
A_{ND}^{(3)} = \frac{f_{e\tau}^* f_{\tau\mu}}{288\pi^2} \frac{1}{m_S^2}
$$

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The Z-penguin contribution

$$F_Z = F_Z^{(1)} + F_Z^{(2)}$$

$$F_Z^{(1)} = -\frac{1}{16\pi^2}\sum_{i=1}^{3}\sum_{(\phi,F_i)}\Big\{g_{ei}^* g_{i\mu}\, g_{ZF_i\overline{F_i}}\,\Big[\Big(2C_{24}(m_\phi, m_{F_i}, m_{F_i}) + \frac{1}{2}\Big) + m_{F_i}^2 C_0(m_\phi, m_{F_i}, m_{F_i})\Big]$$

$$+2\, g_{ei}^* g_{i\mu}\, g_{Z\phi}\, C_{24}(m_{F_i}, m_\phi, m_\phi) + g_{ei}^* g_{i\mu} g_R^l B_1(m_{F_i}, m_\phi)\Big\}$$

$$F_Z^{(2)} = -\frac{1}{16\pi^2} f_{e\tau}^* f_{\tau\mu}\Big\{g_{Z\nu\overline{\nu}}\,\Big(2C_{24}(m_{S_1}, 0, 0) + \frac{1}{2}\Big) + 2g_{ZS_1} C_{24}(0, m_{S_1}, m_{S_1})$$

$$+g_L^l B_1(0, m_{S_1})\Big\}$$

The box contribution can be arranged into three parts,

$$B = B^{(1)} + B^{(2)} + B^{(3)}$$

$$e^2\, B^{(1)} = \frac{1}{16\pi^2}\sum_{i,j=1}^{3}\Big[\frac{\tilde{D}_0}{2} g_{ei}^* g_{i\mu} g_{ej}^* g_{je} + D_0 m_{F_i^0} m_{F_j^0} g_{ei}^* g_{ei}^* g_{j\mu} g_{je}\Big]$$

where, $\tilde{D}_0 = \tilde{D}_0(m_{F_i^0}, m_{F_j^0}, m_{\phi^+}, m_{\phi^+})$ and $D_0 = D_0(m_{F_i^0}, m_{F_j^0}, m_{\phi^+}, m_{\phi^+})$.

$$e^2\, B^{(2)} = \frac{1}{32\pi^2}\sum_{i,j=1}^{3}\sum_{F}\sum_{\phi_1,\phi_2}\tilde{D}_0(m_{F_i}, m_{F_j}, m_{\phi_1}, m_{\phi_2}) g_{ei}^* g_{i\mu} g_{ej}^* g_{je}, \quad e^2 B^{(3)} = -\frac{1}{32\pi^2 m_S^2} f_{e\tau}^* f_{\tau\mu} f_{e\tau}^* f_{\tau e}$$

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The conversion rate, normalized by the muon capture rate is

$$\mathrm{CR}(\mu - e, \mathrm{Nucleus}) = \frac{p_e E_e m_\mu^3 G_F^2 \alpha_{em}^3 Z_{eff}^4 F_p^2}{8\pi^2 Z \Gamma_{\mathrm{capt}}} \Big\{ |(Z+N)(g_{LV}^{(0)} + g_{LS}^{(0)}) + (Z-N)(g_{LV}^{(1)} + g_{LS}^{(1)})|^2$$
$$+ \ |(Z+N)(g_{RV}^{(0)} + g_{RS}^{(0)}) + (Z-N)(g_{RV}^{(1)} + g_{RS}^{(1)})|^2 \Big\}$$

Here, Z and N are the number of protons and neutrons in the nucleus, Z_{eff} is the effective atomic charge, F_p is the nuclear matrix element and Γ_{capt} represents the total muon capture rate. p_e and E_e are the momentum and energy of the electron which is taken as $\sim m_\mu$. $g_{XK}^{(0)}$ and $g_{XK}^{(1)}$ $(X = L, R$ and $K = V, S)$ in the above expression are given as

$$g_{XK}^{(0)} = \frac{1}{2} \sum_{q=u,d,s} (g_{XK(q)} G_K^{(q,p)} + g_{XK(q)} G_K^{(q,n)})$$

$$g_{XK}^{(1)} = \frac{1}{2} \sum_{q=u,d,s} (g_{XK(q)} G_K^{(q,p)} - g_{XK(q)} G_K^{(q,n)})$$

$g_{XK(q)}$ are the couplings in the effective Lagrangian describing $\mu - e$ conversion,

$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} \sum_q \Big\{ [g_{LS(q)} \bar{e}_L \mu_R + g_{RS(q)} \bar{e}_R \mu_L] \bar{q} q + [g_{LV(q)} \bar{e}_L \gamma^\mu \mu_L + g_{RV(q)} \bar{e}_R \gamma^\mu \mu_R] \bar{q} \gamma_\mu q \Big\}$$

$G^{(q,p)}$, $G^{(q,n)}$ are the numerical factors that arise when quark matrix elements are replaced by the nucleon matrix elements,

$$\langle p | \bar{q} \Gamma_K q | p \rangle = G_K^{(q,p)} \bar{p} \Gamma_K p \ , \ \ \langle n | \bar{q} \Gamma_K q | n \rangle = G_K^{(q,n)} \bar{n} \Gamma_K n$$

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The relevant effective coupling for the conversion in this model is

$$g_{LV(q)} = g^{\gamma}_{LV(q)} + g^{Z}_{LV(q)}$$
$$g_{RV(q)} = g_{LV(q)}|_{L\leftrightarrow R}$$
$$g_{LS(q)} \approx 0 \quad , \quad g_{RS(q)} \approx 0$$

The relevant couplings are

$$g^{\gamma}_{RV(q)} = \frac{\sqrt{2}}{G_F} e^2 Q_q \left[(A^{(1)}_{ND} + A^{(2)}_{ND}) - (A^{(1)}_{D} + A^{(2)}_{D})\right], \quad g^{\gamma}_{LV(q)} = \frac{\sqrt{2}}{G_F} e^2 Q_q (A^{(3)}_{ND} - A^{(3)}_{D})$$
$$g^{Z}_{RV(q)} = -\frac{\sqrt{2}}{G_F} \frac{g^q_L + g^q_R}{2} \frac{F^{(1)}_Z}{m^2_Z}, \quad g^{Z}_{LV(q)} = -\frac{\sqrt{2}}{G_F} \frac{g^q_L + g^q_R}{2} \frac{F^{(2)}_Z}{m^2_Z}$$

The decoupling behavior of LFV process,