Indirect upper limits on $\ell_i \to \ell_j\gamma\gamma$ from $\ell_i \to \ell_j\gamma$

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Work in progress in collaboration with

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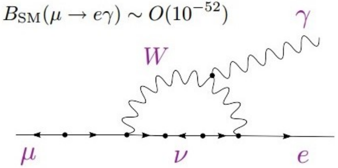
Outline

LFV in the SM

In the SM, lepton flavor violation (LFV) induced by non-zero neutrino masses are too much suppressed to ever be observable.



-BR($Z \to \ell\ell'$) $\sim 10^{-54}$ *J.I. Illana & T. Riemann '01*

-BR($H \to \ell\ell'$) $\sim 10^{-55}$ *E. Arganda et al. '05*

-BR($\mu \to 3e$) $\sim 10^{-54}$, BR($\tau \to 3\ell$) $\sim 10^{-55}$ *Hernández-Tomé et al. '19*

The observation of a charged-lepton flavor violating process would be a definite sign for physics beyond the Standard Model.

https://francis.naukas.com/2014/12/25/la-violacion-del-sabor-en-los-leptones-cargados/dibujo20141225-small-charged-lepton-flavor-violation-fcnc-lepton-sector/

This work

- We consider the cLFV decays of leptons to two photons, $\ell_i \to \ell_j\gamma\gamma$, which have been explored in less detail than other observables such as the single photon $\ell_i \to \ell_j\gamma$, in particular for the case of $\tau \to \ell\gamma\gamma$.
- In order to be model-independent, we work in an effective field theory (EFT) framework.
- We derive new indirect upper limits on the $\ell_i \to \ell_j\gamma\gamma$ decays from the radiatively induced $\ell_i \to \ell_j\gamma$ decays.
- We consider the lowest dimension effective operator generating $\ell_i \to \ell_j\gamma\gamma$ at tree level and compute its one-loop contribution to $\ell_i \to \ell_j\gamma$.

Effective Field Theory

The low-energy effective Lagrangian (QED-invariant) that describes the local interaction of two charged leptons of different flavor, ℓ_i and ℓ_j $(i, j = \tau, \mu, e)$, with two photons is [1]

$$\begin{aligned}
\mathcal{L}_{\rm Int} = & \left(G^{ij}_{SLR} \bar{\ell}_{L_i} \ell_{R_j} + G^{ij}_{SRL} \bar{\ell}_{R_i} \ell_{L_j} \right) F_{\mu\nu} F^{\mu\nu} \\
& + \left(\tilde{G}^{ij}_{SLR} \bar{\ell}_{L_i} \ell_{R_j} + \tilde{G}^{ij}_{SRL} \bar{\ell}_{R_i} \ell_{L_j} \right) \tilde{F}_{\mu\nu} F^{\mu\nu} \\
& + \left(G^{ij}_{VLL} \bar{\ell}_{L_i} \gamma^\sigma \ell_{L_j} + G^{ij}_{VRR} \bar{\ell}_{R_i} \gamma^\sigma \ell_{R_j} \right) F^{\mu\nu} \partial_\nu F_{\mu\sigma} \\
& + \left(\tilde{G}^{ij}_{VLL} \bar{\ell}_{L_i} \gamma^\sigma \ell_{L_j} + \tilde{G}^{ij}_{VRR} \bar{\ell}_{R_i} \gamma^\sigma \ell_{R_j} \right) F^{\mu\nu} \partial_\nu \tilde{F}_{\mu\sigma} \\
& + h.c., \qquad (1)
\end{aligned}$$

[1] Bowman et al. New Upper Limit for $\mu \to e\gamma\gamma$. *Phys. Rev. Lett. 41, 442 (1978).*

Decay rate for $\ell_i \to \ell_j\gamma\gamma$

Considering the scalar dimension seven operators in eq. (1), and neglecting the final lepton mass, the partial decay rate for $\ell_i \to \ell_j\gamma\gamma$ is given by

$$\Gamma(\ell_i \to \ell_j\gamma\gamma) = \frac{|G_{ij}|^2}{3840\pi^3}\, m_i^7\,, \tag{2}$$

with $|G_{ij}|^2 \equiv |G^{ij}_{SRL}|^2 + |G^{ij}_{SLR}|^2 + |\tilde{G}^{ij}_{SRL}|^2 + |\tilde{G}^{ij}_{SLR}|^2$.

Experimental data

Decay Mode	Current upper limit on BR (90%CL)	
$\mu \to e\gamma$	4.2×10^{-13}	MEG (2016) [1]
$\mu \to e\gamma\gamma$	7.2×10^{-11}	Crystal Box (1986) [2]
$\tau \to e\gamma$	3.3×10^{-8}	BaBar (2010) [3]
$\tau \to \mu\gamma$	4.2×10^{-8}	Belle (2021) [4]
$\tau \to \mu\gamma\gamma$	1.5×10^{-4}	ATLAS (2017) [5]

What about $\tau \to e\gamma\gamma$?

No experimental search exist for $\tau \to e\gamma\gamma$. However, recently, Bryman *et al.* [2] recast the searches from BABAR for $\tau \to \ell\gamma$, based on the idea that some of the $\tau \to \ell\gamma\gamma$ events would fall into the $\tau \to \ell\gamma$ signal region.

This analysis found that BR$(\tau \to \mu\gamma\gamma) < 5.8 \times 10^{-4}$ and BR$(\tau \to e\gamma\gamma) < 2.5 \times 10^{-4}$.

[2] Bryman et al.(2021) *Phys. Rev. D 104, 075032.*

Dipole operator

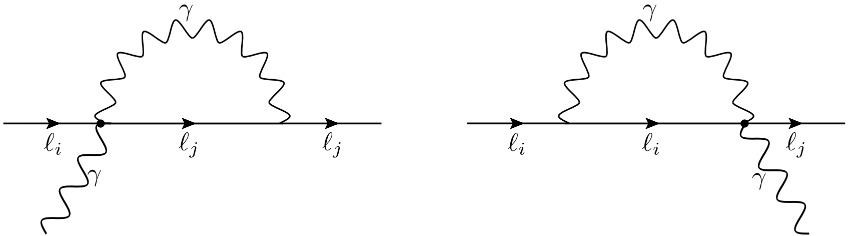
The effective Lagrangian between two charged leptons of different flavor and one photon reads: [3]

$$\mathcal{L}_{\rm Dip} = (C^{ij}_{DR}\bar{\ell}_{R_i}\sigma^{\rho\nu}\ell_{L_j} + C^{ij}_{DL}\bar{\ell}_{L_i}\sigma^{\rho\nu}\ell_{R_j})F_{\rho\nu} + h.c.\,, \tag{3}$$

We can also generate the process $\ell_i \to \ell_j\gamma\gamma$ by means of this effective dipole operator of dimension five and a photon radiated from either lepton. However we are mainly interested in scenarios where $\ell_i \to \ell_j\gamma\gamma$ decays dominate over $\ell_i \to \ell_j\gamma$ decays. So we will disregard this operator for the moment.

[3] A. Celis, V. Cirigliano, and E. Passemar. *Phys. Rev. D* 89, 095014 (2014).

One-loop $\ell_i \to \ell_j\gamma$ from 2-lepton-2-photon effective operator



Decay rate for $\ell_i \to \ell_j\gamma$

Keeping only the leading terms we obtain

$$\Gamma(\ell_i \to \ell_j\gamma) \sim \frac{\alpha|G_{ij}|^2}{256\pi^4} m_i^7 \log^2\left(\frac{\Lambda^2}{m_i^2}\right) , \qquad (4)$$

or, using eq. (2),

$$\Gamma(\ell_i \to \ell_j\gamma) \sim \frac{15\alpha}{\pi} \log^2\left(\frac{\Lambda^2}{m_i^2}\right) \Gamma(\ell_i \to \ell_j\gamma\gamma) . \qquad (5)$$

from where we can derive indirect upper limits for $\ell_i \to \ell_j\gamma\gamma$ from the upper limits on $\ell_i \to \ell_j\gamma$.

Comparison between branching fractions

Decay Mode	Current upper limit on BR (90%CL)	
$\mu \to e\gamma$	4.2×10^{-13}	MEG (2016) [1]
$\mu \to e\gamma\gamma$	7.2×10^{-11}	Crystal Box (1986) [2]
$\tau \to e\gamma$	3.3×10^{-8}	BaBar (2010) [3]
$\tau \to \mu\gamma$	4.2×10^{-8}	Belle (2021) [4]
$\tau \to \mu\gamma\gamma$	1.5×10^{-4}	ATLAS (2017) [5]

We obtain

$$
\begin{aligned}
\mathrm{BR}(\mu \to e\gamma\gamma) &\lesssim 6.4 \times 10^{-14} \left[1 + 0.15 \log \frac{\Lambda}{100\mathrm{GeV}}\right]^{-2}, \\
\mathrm{BR}(\tau \to e\gamma\gamma) &\lesssim 1.5 \times 10^{-8} \left[1 + 0.25 \log \frac{\Lambda}{100\mathrm{GeV}}\right]^{-2}, \\
\mathrm{BR}(\tau \to \mu\gamma\gamma) &\lesssim 1.9 \times 10^{-8} \left[1 + 0.25 \log \frac{\Lambda}{100\mathrm{GeV}}\right]^{-2}.
\end{aligned}
\tag{6}
$$

$\Lambda = 100$ GeV, $\Lambda = 1$ TeV

Taking $\Lambda = 100$ GeV

$$\begin{aligned} \mathrm{BR}(\mu \to e\gamma\gamma) &\lesssim 6.4 \times 10^{-14}\,, \\ \mathrm{BR}(\tau \to e\gamma\gamma) &\lesssim 1.5 \times 10^{-8}\,, \\ \mathrm{BR}(\tau \to \mu\gamma\gamma) &\lesssim 1.9 \times 10^{-8}\,. \end{aligned} \tag{7}$$

Taking $\Lambda = 1$ TeV

$$\begin{aligned} \mathrm{BR}(\mu \to e\gamma\gamma) &\lesssim 3.5 \times 10^{-14}\,, \\ \mathrm{BR}(\tau \to e\gamma\gamma) &\lesssim 6.0 \times 10^{-9}\,, \\ \mathrm{BR}(\tau \to \mu\gamma\gamma) &\lesssim 7.7 \times 10^{-9}\,. \end{aligned} \tag{8}$$

Processes $\ell_i \to \ell_j \bar{\ell}_k \ell_k$

Processes $\ell_i \to \ell_j \bar{\ell}_k \ell_k$ are $\mathcal{O}(\alpha)$ suppressed compared with the $\ell_i \to \ell_j \gamma$ decays.

Since the experimental constraints on both types of processes are of the same order, then restrictions on $\ell_i \to \ell_j \bar{\ell}_k \ell_k$ are trivially satisfied when the limits on $\ell_i \to \ell_j \gamma$ have been imposed.

$BR(\mu \to 3e) < 1.0 \times 10^{-12}$, $BR(\tau \to 3\ell) \lesssim 10^{-8}$. [4]

[4] R.L. Workman et al. (Particle Data Group), *Prog. Theor. Exp. Phys. 2022, 083C01 (2022)*.

About UV Completion

An interesting possibility arises in models where the cLFV is mediated by heavy scalars, such as a two Higgs doublet model (2HDM) with off-diagonal Yukawa interactions.

In this scenario, $\ell_i \to \ell_j \gamma$ decays are induced at one-loop level, however they are suppressed by three chiral flips and therefore the two-loop (Barr-Zee diagrams) contributions are actually the dominant ones. [5]

On the other hand, the $\ell_i \to \ell_j \gamma\gamma$ decays do not suffer from this chirality suppression, the dominant contributions are at the one-loop and, consequently, they can have ratios comparable to those of $\ell_i \to \ell_j \gamma$.

[5] Hisano et al. (2011) *Physics Letter B 694, 380*.

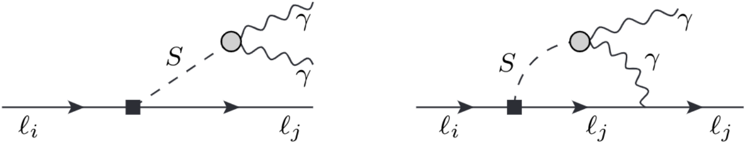


Figure: Example of diagrams generating $\ell_i \to \ell_j\gamma\gamma$ and $\ell_i \to \ell_j\gamma$ mediated by a scalar with off-diagonal Yukawa couplings and an effective vertex to two photons.

In the heavy scalar limit the diagram on the left reduces to a local interaction.

We have checked that —in the heavy scalar limit— both the single and double photon decay modes would have similar probabilities.

This is a well-motivated scenario that illustrates the potential of $\ell_i \to \ell_j\gamma\gamma$ decays in the search for new physics.

Conclusions

- Following an EFT analysis, we derived model-independent upper limits for $\ell_i \to \ell_j\gamma\gamma$.
- These upper limits were obtained in the most favored situation for the double photon channel, where dim-7 operators dominate over dim-5 ones, and thus we could consider them as the most conservative limits. Still, our results go beyond the current knowledge about these decays.
- From the EFT point of view, the decays $\ell_i \to \ell_j\gamma\gamma$ can be driven by new independent effective operators, and thus they will help covering directions in the new physics space.

Thanks for your attention

Bibliography

[1] A. Baldini **et al.** (MEG), *Eur. Phys. J. C 76, 434 (2016)*.
[2] D.Grosnick *et al.*, *Phys. Rev. Lett. 57, 3241 (1986)*.
[3] B. Aubert *et al.* (BaBar), *Phys. Rev. Lett. 104, 021802 (2010), arXiv:0908.2381 [hep-ex]*.
[4] A. Abdesselam *et al.* (Belle), *(2021), arXiv:2103.12994 [hep-ex].*
[5] I. Angelozzi. In pursuit of lepton flavor violation: A search for the $\tau \to \mu\gamma\gamma$ decay with ATLAS at $\sqrt{s} = 0$ TeV. *Ph.D. Thesis, U. Amsterdam, IHEF (2017)*

Counterterms

The amplitudes generated by these diagrams have UV divergent terms, and thus we need to introduce dimension 5 and 6 counterterms to absorb them. These are given by

$$\mathcal{L}_{\text{CT}} = C_{LL}\,\bar{\ell}_L\gamma^\alpha\partial^\beta\ell_L F_{\alpha\beta} + C_{RR}\,\bar{\ell}_R\gamma^\alpha\partial^\beta\ell_R F_{\alpha\beta} + D_{LR}\,\bar{\ell}_L\sigma_{\alpha\beta}\ell_R F^{\alpha\beta} + D_{RL}\,\bar{\ell}_R\sigma_{\alpha\beta}\ell_L F^{\alpha\beta}\,. \tag{9}$$

The coefficients of these operators take the values

$$C_{LL} = \frac{2\,e}{3\epsilon} m_i\,(\tilde{G}_{LR} - iG_{LR})\,, \qquad C_{RR} = -\frac{2\,e}{3\epsilon} m_i\,(\tilde{G}_{RL} - iG_R L)\,,$$
$$D_{LR} = \frac{2\,e}{3\epsilon} m_i^2\,(2i\tilde{G}_{LR} - G_{LR})\,, \qquad D_{RL} = -\frac{2\,e}{3\epsilon} m_i^2\,(2i\tilde{G}_{RL} - G_{RL})\,,$$

with $D = 4 - 2\epsilon$.