Exploring hadronic de-excitation via Lepton Flavor Violation

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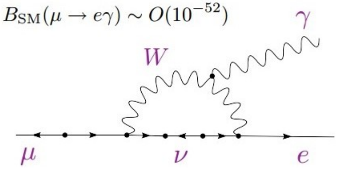
Contents

Motivation

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.

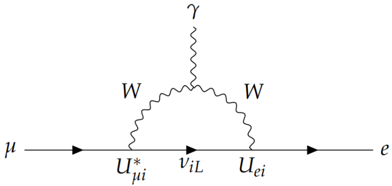


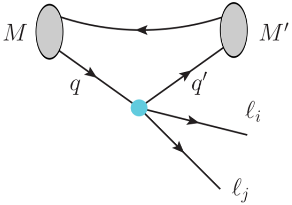
-BR$(Z \to \ell\ell') \sim 10^{-54}$ *J.I. Illana & T. Riemann '01*
-BR$(H \to \ell\ell') \sim 10^{-55}$ *E. Arganda et al. '05*
-BR$(\mu \to 3e) \sim 10^{-54}$, BR$(\tau \to 3\ell) \sim 10^{-55}$ *Hernández-Tomé et al. '19*

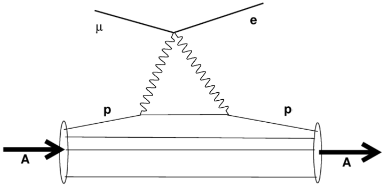
The observation of a charged-lepton flavor violating process would be a definite sign for physics beyond the Standard Model. [1]

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

LFV searches [2]







We study $\rho' \to \rho\mu e$ decay. Determine at which extent they can offer new features of LFV in low energy hadronic states.

[2] *Riv.Nuovo Cim. 41 (2018) 2, 71-174. Eur.Phys.J.C 83 (2023) 8, 753. Phys.Rev.D 102 (2020) 11, 115043.*

Introduction (EFT)

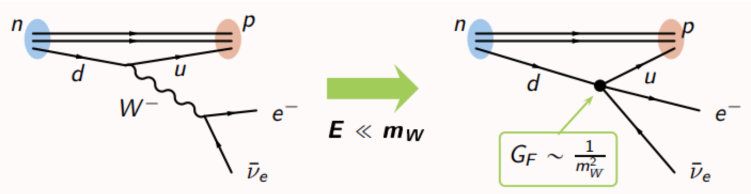
Effective Field Theories [3]

A pragmatic definition: It's a field theory that describes the **IR limit** of an underlying UV sector in terms of only the light degrees of freedom.

A classical example: Fermi's interaction for β-decays

"True" theory: Weak interaction

EFT: Fermi's interaction



[3] https://indico.cern.ch/event/846927/contributions/3623943/attachments/1955984/3250585/slides_VBS_Lisbon-2.pdf.

Effective Field Theories

Let $\mathcal{P}$ be the physics at Λ scale,

- $\mathcal{P}$ effects at $E \ll \Lambda$ are described by local, analytic operators with suppressions $1/\Lambda^n$.
- Taylor expansion in (E/Λ) at the Lagrangian level.
- The EFT allows us to compute matrix elements without knowing the UV.

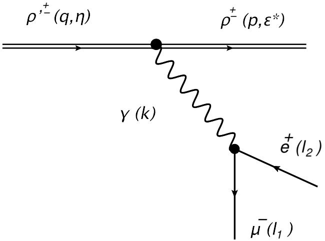
  Inputs: Light fields & symmetries

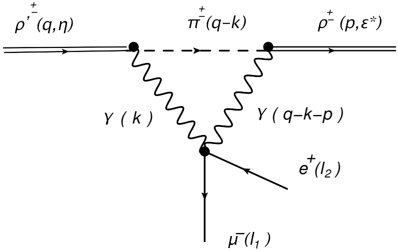
$$\mathcal{L}_{\text{EFT}} = \sum_i C_i \mathcal{O}_i \,, \tag{1}$$

where C_i are free parameters (Wilson coefficients), $\mathcal{O}_i$ are invariant operators that form a complete, non-redundant basis.

Decay calculation

Diagrams $\rho' \to \rho\mu^- e^+$



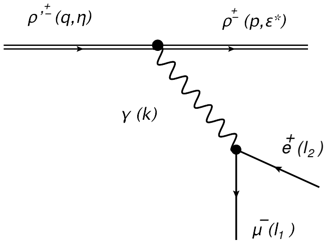


- Hadronic side: Vector Meson Dominance model (VMD).
- Leptonic side: Effective field theory (LEFT, below the electroweak scale).

$$\mathcal{L}_{\text{dim-5}} = D_R^{\mu e}\,\bar{\mu}_L\sigma_{\mu\nu}e_R F^{\mu\nu} + D_L^{\mu e}\,\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.\,, \tag{2}$$

$$\begin{aligned}\mathcal{L}_{\text{dim-7}} &= \left(G_{SR}^{\mu e}\bar{\mu}_L e_R + G_{SL}^{\mu e}\bar{\mu}_R e_L\right) F_{\mu\nu}F^{\mu\nu} \\ &+ \left(\tilde{G}_{SR}^{\mu e}\bar{\mu}_L e_R + \tilde{G}_{SL}^{\mu e}\bar{\mu}_R e_L\right) \tilde{F}_{\mu\nu}F^{\mu\nu} + \text{h.c.}\,,\end{aligned} \tag{3}$$

Tree level diagram



$$\mathcal{M}_{\rm dim5} = -\frac{e\, g_{\rho'\rho\gamma}}{k^2}\ell_{\mu\nu}(k^\mu g^{\nu\gamma} - k^\nu g^{\mu\lambda})\Gamma_{\alpha\beta\gamma}(q,k)\eta^\alpha\epsilon^{*\beta}\,. \quad (4)$$

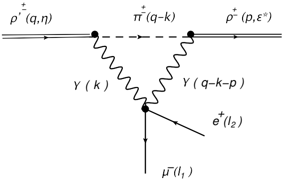
$\ell_{\mu\nu} = \bar{u}_1\sigma_{\mu\nu}(D_R^{\mu e}P_R + D_L^{\mu e}P_L)v_2$. The global strength is set by $eg_{\rho'\rho\gamma}$, where the $g_{\rho'\rho\gamma}$ coupling is taken as the ratio of the g_ρ and $g_{\rho'}$ couplings (g_V accounts for the vector interaction with the photon) [4].

$$\Gamma_{\alpha\beta\gamma}(q,k) = \beta(g^{\alpha\beta}k^\alpha - g^{\gamma\alpha}k^\beta) + \frac{\gamma}{2m_{\rho'}^2}\left[(2q-k)^\gamma k^\alpha k^\beta - q\cdot k(g^{\beta\gamma}k^\alpha + g^{\gamma\alpha}k^\beta)\right]. \quad (5)$$
[5]

[4] Gustavo Ávalos, Antonio Rojas, Marxil Sánchez, and Genaro Toledo. *Phys. Rev. D 107, 056006.*

[5] Jose F. Nieves and Palash B. Pal. *Phys.Rev.D 55 (1997) 3118-3130.*

One-loop level diagram



$$\mathcal{L} = g_{VP\gamma}\epsilon_{\alpha\beta\mu\nu}\partial^\alpha V^\beta \partial^\mu A^\nu P\,, \tag{6}$$

$$\mathcal{M}_{\text{dim7}(F)} = 2\ell^F\Gamma^F_{\alpha\beta}\eta^\alpha\epsilon^{*\beta}, \qquad \ell^F = \bar{u}_1(G^{\mu e}_{SR}P_R + G^{\mu e}_{SL}P_L)v_2. \tag{7}$$

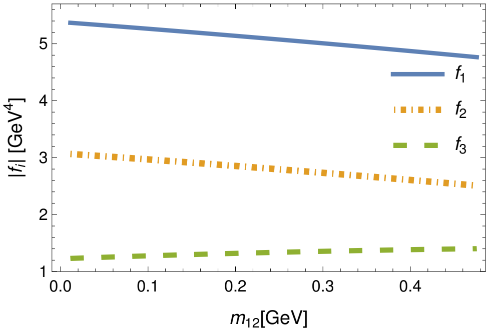
$$\mathcal{M}_{\text{dim7}(\tilde{F})} = 2\ell^{\tilde{F}}\Gamma^{\tilde{F}}_{\alpha\beta}\eta^\alpha\epsilon^{*\beta}, \qquad \ell^{\tilde{F}} = \bar{u}_1(\tilde{G}^{\mu e}_{SR}P_R + \tilde{G}^{\mu e}_{SL}P_L)v_2. \tag{8}$$

$$\Gamma^F_{\alpha\beta} = \frac{ig_{\rho'\pi\gamma}\,g_{\rho\pi\gamma}}{16\pi^2}\left\{f_1(m^2_{12})p_\alpha q_\beta + f_2(m^2_{12})g_{\alpha\beta}\right\}\,, \tag{9}$$

$$\Gamma^{\tilde{F}}_{\alpha\beta} = \frac{ig_{\rho'\pi\gamma}\,g_{\rho\pi\gamma}}{16\pi^2}\epsilon_{\alpha\beta\mu\nu}p^\mu q^\nu f_3(m^2_{12})\,. \tag{10}$$

The $g_{VP\gamma}$ couplings can be obtained using VMD relations between radiative and hadronic couplings, $g_{\rho(\rho')\pi\gamma} = g_{\rho(\rho')\omega\pi}e/g_\omega$ (again values from *Phys. Rev. D 107, 056006*).

Comparing loop functions



$$\Gamma^{F}_{\alpha\beta} = \frac{i g_{\rho'\pi\gamma}\, g_{\rho\pi\gamma}}{16\pi^2} \left\{ f_1(m_{12}^2) p_\alpha q_\beta + f_2(m_{12}^2) g_{\alpha\beta} \right\} ,$$

$$\Gamma^{\tilde{F}}_{\alpha\beta} = \frac{i g_{\rho'\pi\gamma}\, g_{\rho\pi\gamma}}{16\pi^2} \epsilon_{\alpha\beta\mu\nu} p^\mu q^\nu f_3(m_{12}^2) \, . \tag{11}$$

($|f_1|$ and $|f_3|$ are multiplied by $p \cdot q$ to be dimensionally consistent.)

Constraints for $D^{\mu e}$ and $G^{\mu e}$

Taking the decay rates computed previously [6]

$$\Gamma(\mu \to e\gamma)\big|_{\text{dim}-5} = \frac{m_\mu^3}{4\pi}\left|D^{\mu e}\right|^2 ,$$
$$\Gamma(\mu \to e\gamma)\big|_{\text{dim}-7} \sim \frac{\alpha\left|G_{\mu e}\right|^2}{256\pi^4} m_\mu^7 \log^2\left(\frac{\Lambda^2}{m_\mu^2}\right) , \quad (12)$$

where $\left|D^{\mu e}\right|^2 = \left|D_R^{\mu e}\right|^2 + \left|D_L^{\mu e}\right|^2$ and $\left|G_{\mu e}\right|^2 = \left|G_{SR}^{\mu e}\right|^2 + \left|G_{SL}^{\mu e}\right|^2 + \left|\tilde{G}_{SR}^{\mu e}\right|^2 + \left|\tilde{G}_{SL}^{\mu e}\right|^2$, and the current upper limit on the $\mu \to e\gamma$ decay, BR$(\mu \to e\gamma) < 3.1 \times 10^{-13}$ at 90%CL [7], we obtain

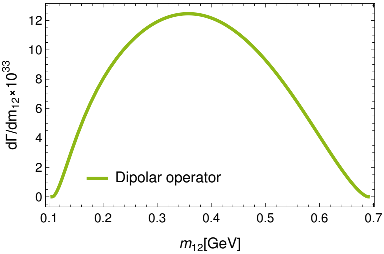
Coefficient	Constraint
$\left\|D^{\mu e}\right\|$	3.1×10^{-14} GeV^{-1}
$\left\|G_{\mu e}\right\|$	1.1×10^{-10} GeV^{-3}

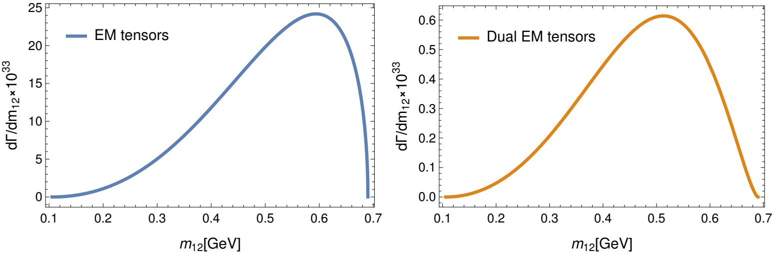
[6] Fabiola Fortuna, Alejandro Ibarra, Xabier Marcano, Marcela Marín, Pablo Roig. *Phys.Rev.D 107 (2023) 1, 015027.*

[7] MEG II Collaboration. K. Afanaciev et al. *Eur.Phys.J.C 84 (2024) 3, 216.*

Results & Discussion

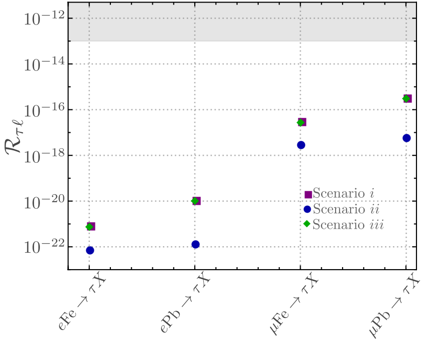
Dilepton invariant mass distributions





Branching ratios

Operator	BR($\rho' \to \rho\mu e$)
Dim-5 dipolar	$[1.7 - 77.8] \times 10^{-33}$
Dim-7 EM	1.7×10^{-32}
Dim-7 Dual EM	4.4×10^{-34}



$\ell \to \tau$ conversion in nuclei

(DIS process)

- Scenario ii: Dim-7 EM
- Scenario iii: Dim-7 Dual EM

Phys.Rev.D 108 (2023) 1, 015008.

Conclusions

Conclusions

- In this work we have explored a particular case of hadronic de-excitation via LFV and the different features they can exhibit, depending on the effective operator producing the LFV pair.
- Low energy experiments are reaching a high luminosity stage where this kind of hadrons are copiously produced, which opens the possibility to explore this type of scenarios not yet considered.
- The results may be useful to disentangle individual contributions when complemented with observables from nuclei.
- Our particular case can be taken as an initial step to look for the de-excitation of other hadronic states, such as in quarkonia.

Thank you!