“Lepton flavor violation via $e \to \tau$ conversion in nuclei at the EIC"

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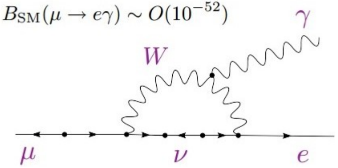
Content

Motivation

cLFV in the SM

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

$$B_{\rm SM}(\mu \to e\gamma) \sim O(10^{-52})$$



-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.
- cLFV processes offer the possibility to “diagnose” the underlying new physics and its effect on neutrino mass generation.

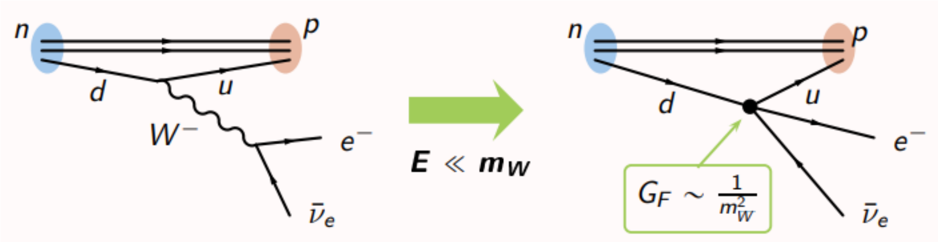
Effective Field Theories

Effective Field Theories [1]

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



The EFT allows us to compute matrix elements without knowing the UV.

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

Effective Lagrangian

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 [2]

$$
\begin{aligned}
\mathcal{L}_{\text{Int}} = & \left(G_{SR}^{ij} \bar{\ell}_{L_i} \ell_{R_j} + G_{SL}^{ij} \bar{\ell}_{R_i} \ell_{L_j} \right) F_{\mu\nu} F^{\mu\nu} \\
& + \left(\tilde{G}_{SR}^{ij} \bar{\ell}_{L_i} \ell_{R_j} + \tilde{G}_{SL}^{ij} \bar{\ell}_{R_i} \ell_{L_j} \right) \tilde{F}_{\mu\nu} F^{\mu\nu} \\
& + h.c. \,, \qquad (1)
\end{aligned}
$$

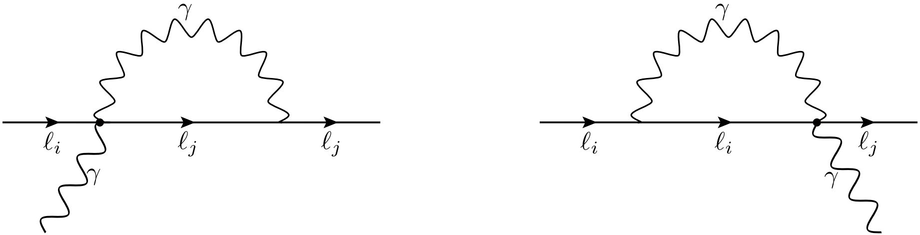
[2] Bowman et al. *Phys. Rev. Lett. 41, 442 (1978).*

Constraint for $G_{\tau e}$ Wilson coefficient

Currently, the most stringent bound for this coefficient comes from the experimental upper limit [3] on

$$\text{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}, \qquad \text{BaBar}(2010).$$

We compute the one-loop $\tau \to e\gamma$ from 2-lepton-2-photon effective operator



[3] BaBar Collaboration. Bernard Aubert et al. *Phys.Rev.Lett. 104 (2010) 021802*

Constraint for $G_{\tau e}$ Wilson coefficient

The $\ell_i \to \ell_j\gamma$ is generated at one loop level

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

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

Taking $\Lambda = 10$ TeV, we obtain

$$|G_{\tau e}| = 3.9 \times 10^{-9}\,\text{GeV}^{-3}\,. \tag{3}$$

$\ell \to \tau$ conversion in nuclei

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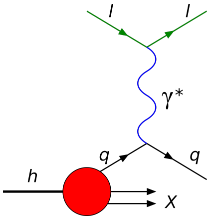
The conversion is expected to occur by DIS of the lepton off the nucleus, meaning that the energy is high enough as to break the nucleons within the nucleus and interact with its partons, i.e., quarks and gluons.



We focus on inclusive processes, whose products of interaction are a τ lepton plus any hadrons, i.e., $\ell + \mathcal{N} \to \tau + X$, where we do not have any information about X [4].

[4] Husek et al. Lepton-flavour violation in hadronic tau decays and $\mu - \tau$ conversion in nuclei. *JHEP 01 (2021) 059.*

Total cross section

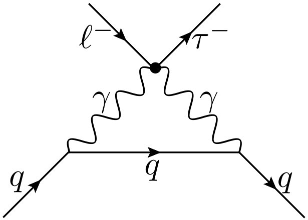
Using the QCD factorization theorems, we can obtain the total cross section by calculating the convolution

$$\sigma_{\ell-\tau} = \hat{\sigma}(\xi, Q^2) \otimes f(\xi, Q^2)\,, \tag{4}$$ [5]

- Q^2 is the characteristic energy scale, typically related to the transferred momentum q^2 of the system as $Q^2 = -q^2$.
- ξ is the fraction of the nucleus momentum carried by the interacting parton.
- $\hat{\sigma}$, perturbative cross section.
- f, nonperturbative PDFs.

[5] The evolution of the PDFs in terms of Q^2 is achieved by using the DGLAP evolution equations, whose dependence on the momentum fraction ξ is completely nonperturbative and has to be extracted from the data.

Contributions to the perturbative cross section



- $\ell q \to \tau q$ process.
- Same process with antiquarks: $\ell\bar{q} \to \tau\bar{q}$. The nonperturbative behavior of antiquarks inside the nucleons differs from their opposite-charged partners, and also the perturbative cross sections of the process are different from those involving quarks.

Differential cross section

$$\overline{|\mathcal{M}_{qq}(\xi,Q^2)|^2} = 6e^4\left(|G_{SR}^{\tau\ell}|^2 + |G_{SL}^{\tau\ell}|^2\right)\left[\left(m_\ell^2 + m_\tau^2 + Q^2\right)\left((m_i + \xi M)^2 + Q^2\right)\right]\Gamma_{qq}(\xi,Q^2)$$
$$+ \frac{3e^4}{2}\left(|\tilde{G}_{SR}^{\tau\ell}|^2 + |\tilde{G}_{SL}^{\tau\ell}|^2\right)\left[\left(m_\ell^2 + m_\tau^2 + Q^2\right)\left((m_i - \xi M)^2 + Q^2\right)\right]\tilde{\Gamma}_{qq}(\xi,Q^2)\,. \qquad (5)$$

where $\Gamma_{qq}(\xi,Q^2)$ and $\tilde{\Gamma}_{qq}(\xi,Q^2)$ are the functions obtained from the loop evaluation.

For the numerical analysis we establish three benchmark scenarios:

$$(i)\ |G_{\tau\ell}|^2 = |G_{SR}^{\tau\ell}|^2 + |G_{SL}^{\tau\ell}|^2 = |\tilde{G}_{SR}^{\tau\ell}|^2 + |\tilde{G}_{SL}^{\tau\ell}|^2\,,$$
$$(ii)\ |G_{\tau\ell}|^2 = |G_{SR}^{\tau\ell}|^2 + |G_{SL}^{\tau\ell}|^2;\ \tilde{G}_{SR}^{\tau\ell} = \tilde{G}_{SL}^{\tau\ell} = 0\,,$$
$$(iii)\ |G_{\tau\ell}|^2 = |\tilde{G}_{SR}^{\tau\ell}|^2 + |\tilde{G}_{SL}^{\tau\ell}|^2;\ G_{SR}^{\tau\ell} = G_{SL}^{\tau\ell} = 0\,. \qquad (6)$$

$\mathcal{R}_{\tau\ell}$ ratio

Finally we compute

$$\sigma(\ell\mathcal{N}(P) \to \tau X) = \sum_i \int_{\xi_{\text{min}}}^{1} \int_{Q_-^2(\xi)}^{Q_+^2(\xi)} d\xi dQ^2 \left\{ \frac{d\hat{\sigma}(\ell\, q_i(\xi P) \to \tau\, q_i)}{d\xi\, dQ^2} f_{q_i}(\xi, Q^2) + \frac{d\hat{\sigma}(\ell\, \bar{q}_i(\xi P) \to \tau\, \bar{q}_i)}{d\xi dQ^2} f_{\bar{q}_i}(\xi, Q^2) \right\}, \quad (7)$$

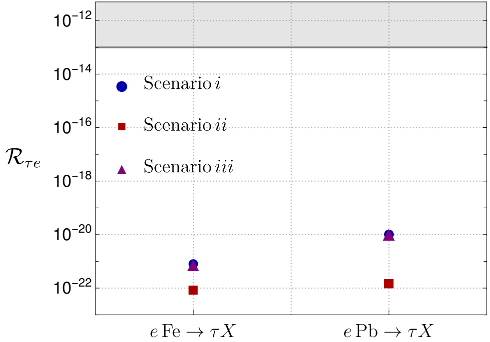
The relevant quantity in this case is given by the ratio of the cross sections of two inclusive processes

$$\mathcal{R}_{\tau\ell} = \frac{\sigma(\ell\mathcal{N} \to \tau X)}{\sigma(\ell\mathcal{N} \to \ell X)}, \quad (8)$$

where the denominator is given by the dominant contribution to the inclusive $\ell + \mathcal{N}$ process as a result of lepton bremsstrahlung on nuclei.

Results for NA64 prospects

- We use $E_e = 100\,$GeV for the energy of the incident e beam [6]. The most conservative expected sensitivity of the NA64 experiment is $\mathcal{R}_{\tau\ell} \sim [10^{-13}, 10^{-12}]$.



[6] Sergei Gninenko et al. Deep inelastic $e-\tau$ and $\mu-\tau$ conversion in the NA64 experiment at the CERN SPS. *Phys.Rev.D 98 (2018) 1, 015007*.

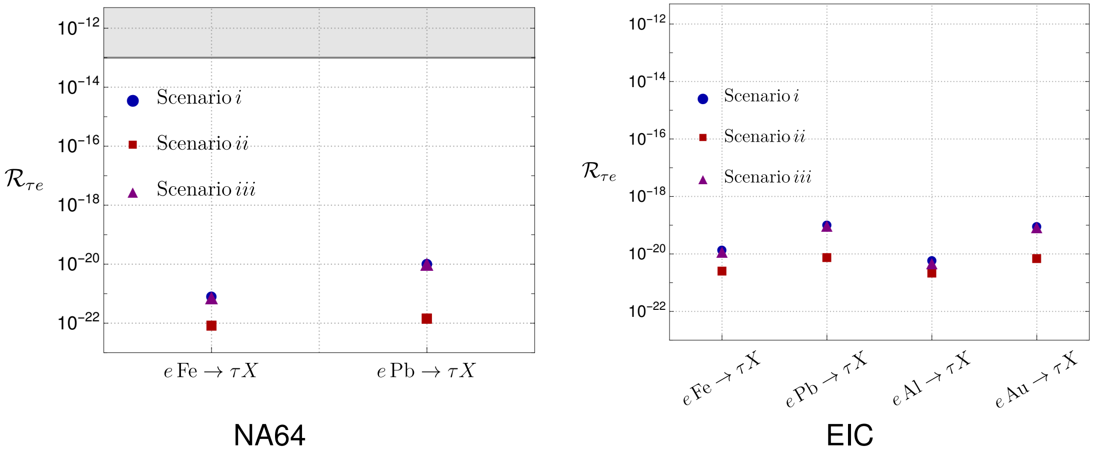
EIC reference values

- Ion beams from deuterons to the heaviest stable nuclei.

Ion	CM energy per nucleon	Energy of e-beam in Lab frame
Fe	95 GeV	4.19 TeV
Pb	89 GeV	4.15 TeV
Al	95 GeV	4.83 TeV
Au	89 GeV	4.16 TeV

Electron-Ion Collider Collaboration, *Electron-Ion Collider Global Requirements*, 2023. Available at: https://eic.jlab.org/Documents/EIC-SEG/Electron-Ion%20Collider%20Global%20Requirements.pdf

Results for EIC prospects an comparison with NA64



Fabiola Fortuna et al. *Phys.Rev.D 108 (2023) 1, 015008.*

Conclusions

Conclusions

- Effective field theories are very useful tools to study physics beyond the standard model.
- We computed the $e \to \tau$ conversion process using the expected beam energies and target nuclei for the NA64 experiment and the EIC, and compared the results.
- The EIC could achieve results up to one order of magnitude better than those of the NA64 experiment for $e \to \tau$ conversion in nuclei.

Thank you