

Lepton flavor violation in photon-induced electron-muon pairs at the HL-LHC

M. A. Arroyo-Ureña^{1,2,*}, O. Félix-Beltrán^{3,†}, J. Hernández-Sánchez^{3,‡},
C. G. Honorato^{3,§} and S. Rosado-Navarro^{1,2,||}

¹*Facultad de Ciencias Físico-Matemáticas, Benemérita Universidad Autónoma de Puebla, Apartado Postal 1152, C.P. 72560, Puebla, Puebla, México*

²*Centro Interdisciplinario de Investigación y Enseñanza de la Ciencia (CIEC), Benemérita Universidad Autónoma de Puebla, C.P. 72570, Puebla, Puebla, México*

³*Facultad de Ciencias de la Electrónica, Benemérita Universidad Autónoma de Puebla, Apartado Postal 1152, C.P. 72570, Puebla, Puebla, México*



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We show the outstanding potential of the High-Luminosity LHC (HL-LHC) to discover charged lepton flavor violation (cLFV) via the ultraperipheral process $\gamma\gamma \rightarrow e^\pm\mu^\mp$. Using a gauge-invariant effective field theory framework—consistent with the most stringent bounds from radiative decays—we perform a full Monte Carlo analysis with multivariate techniques. Our results show that a 5σ discovery is achievable with an integrated luminosity of $\mathcal{L}_{\text{int}} \gtrsim 2700 \text{ fb}^{-1}$ for favorable benchmark scenarios. This study establishes photon fusion at the HL-LHC as a powerful probe of cLFV, strongly motivating dedicated searches by the experimental collaborations.

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Introduction. In the Standard Model (SM), lepton flavor violation (LFV) is strictly forbidden. However, the observation of neutrino oscillations has confirmed that such particles have nonzero masses, which introduces LFV in the neutral sector. Within the SM framework, charged lepton flavor violation (cLFV) processes remain highly suppressed due to the Glashow-Iliopoulos-Maiani mechanism. Consequently, any experimental observation of a cLFV process would constitute unambiguous evidence for physics beyond the SM (BSM). In this work, we aim to explore the $\gamma\gamma e\mu$ interaction within an effective field theory (EFT) framework and assess its prospects for experimental scrutiny at the High-Luminosity LHC (HL-LHC) [1]. An analogous method, but in e^-e^+ colliders, is studied in [2]. This strategy leverages photon-photon interactions in ultraperipheral collisions (UPCs), where these types of interactions provide a pristine environment for studying electromagnetic phenomena, as they are precisely described

by quantum electrodynamics and can be efficiently modeled using the equivalent photon approximation.

A confrontation of the EFT predictions against current experimental bounds shows that the most stringent constraint on the diphoton operators originates from the loop-induced radiative decays $\mu \rightarrow e\gamma$ [3]. However, even after accommodating this constraint by suppressing the relevant theory parameters, a viable region of parameter space is found, providing strong motivation for experimental searches.

Theoretical framework. The local cLFV $\gamma\gamma\bar{\ell}_i\ell_j$ interaction is described by the effective Lagrangian [4]

$$\mathcal{L}_{\text{eff}} = (G_{SR}^{ij}\bar{\ell}_{L_i}\ell_{R_j} + G_{SL}^{ij}\bar{\ell}_{R_i}\ell_{L_j})F_{\mu\nu}F^{\mu\nu} + (\tilde{G}_{SR}^{ij}\bar{\ell}_{L_i}\ell_{R_j} + \tilde{G}_{SL}^{ij}\bar{\ell}_{R_i}\ell_{L_j})\tilde{F}_{\mu\nu}F^{\mu\nu} + \text{H.c.}, \quad (1)$$

where $\ell_i, \ell_j = e, \mu, \tau$ denote the lepton flavors, $F_{\mu\nu}$ is the electromagnetic field strength tensor, and $\tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\sigma\lambda}F^{\sigma\lambda}$ is its dual. The couplings G_{SR}^{ij} , G_{SL}^{ij} , $\tilde{G}_{SR}^{ij}$, and $\tilde{G}_{SL}^{ij}$ are dimensionful, scaling as Λ^{-3} , where Λ is the energy cutoff of the EFT. This scaling is characteristic of dimension-seven operators in an EFT extension of the SM, where LFV processes are forbidden at tree level but can be induced in scenarios BSM.

The free effective coupling that has a direct impact on the process $\gamma\gamma e\mu$ is controlled by $|G_{e\mu}|$. This effective coupling encapsulates the relevant operator coefficients and can be written as

*Contact author: marco.arroyo@cfm.buap.mx

†Contact author: olga.felix@correo.buap.mx

‡Contact author: jaime.hernandez@correo.buap.mx

§Contact author: carlos.g.honorato@correo.buap.mx

||Contact author: sebastian.rosado@protonmail.com

$$|G_{e\mu}|^2 = 2(|G_P^{e\mu}|^2 + |G_S^{e\mu}|^2 + |\tilde{G}_P^{e\mu}|^2 + |\tilde{G}_S^{e\mu}|^2), \quad (2)$$

where

$$\begin{aligned} G_S^{e\mu} &= \frac{G_{SR}^{e\mu} + G_{SL}^{e\mu}}{2}, & G_P^{e\mu} &= \frac{G_{SR}^{e\mu} - G_{SL}^{e\mu}}{2}, \\ \tilde{G}_S^{e\mu} &= \frac{\tilde{G}_{SR}^{e\mu} + \tilde{G}_{SL}^{e\mu}}{2}, & \tilde{G}_P^{e\mu} &= \frac{\tilde{G}_{SR}^{e\mu} - \tilde{G}_{SL}^{e\mu}}{2}. \end{aligned} \quad (3)$$

From the upper limit on $\text{BR}(\mu \rightarrow e\gamma)$, a stringent constraint on the effective coupling $|G_{e\mu}|$ is found [5]:

$$|G_{e\mu}| \lesssim 1.2 \times 10^{-10} \left(1 + 0.15 \ln \frac{\Lambda}{100 \text{ GeV}} \right)^{-1} \text{ GeV}^{-3}. \quad (4)$$

From Eqs. (4) and (2), we obtain the parameter space presented in Fig. 1.

For this study, we select the benchmark values of the cutoff scale such as $\Lambda \gg \sqrt{s_{\gamma\gamma}}$, where $\sqrt{s_{\gamma\gamma}}$ is the center-of-mass energy of the $\gamma\gamma$ system. This choice is motivated by the requirement that the EFT expansion remains consistent; specifically, for $\Lambda \gtrsim 2\sqrt{s_{\gamma\gamma}}$, contributions from a dimension- d operator are suppressed by at least $(\sqrt{s_{\gamma\gamma}}/\Lambda)^{d-4}$, ensuring that nonrenormalizable terms remain under control. The center-of-mass energy required to produce an $e\mu$ pair is $\sqrt{s_{\gamma\gamma}} \gtrsim m_\mu$, which might naively suggest that a low effective scale Λ could suffice. However, values of $\Lambda \lesssim 100 \text{ GeV}$ are incompatible with the EFT framework, as they would invalidate its core assumption that Λ is significantly larger than the energy scale of the process. In fact, such a low Λ would imply the existence of new particles with masses near or below the electroweak scale, which would require their explicit inclusion in the SM rather than a description through effective operators.

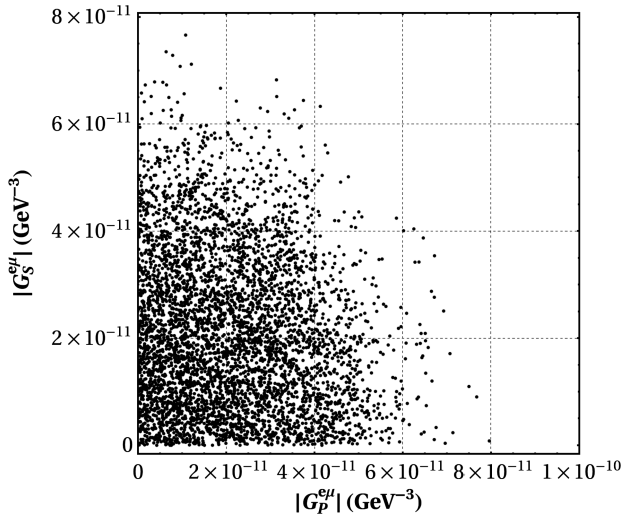


FIG. 1. Parameter space in the $|G_S^{e\mu}| - |G_P^{e\mu}|$. We scan the intervals $|G_{S,P}^{e\mu}|, |\tilde{G}_{S,P}^{e\mu}| \in [0, 10^{-9}] \text{ GeV}^{-3}$, and $\Lambda \in (100, 5000) \text{ GeV}$. The black points represent those allowed by the constraints in Eqs. (4) and (2).

Accordingly, we will explore three benchmark points (BPs) to span the viable parameter space:

(i) BP1: $\Lambda = 1048 \text{ GeV}$

$$\begin{aligned} |G_S^{e\mu}| &= 3.85 \times 10^{-11} \text{ GeV}^{-3}, \\ |G_P^{e\mu}| &= 4.25 \times 10^{-11} \text{ GeV}^{-3}, \\ |\tilde{G}_S^{e\mu}| &= 1.91 \times 10^{-12} \text{ GeV}^{-3}, \\ |\tilde{G}_P^{e\mu}| &= 2.42 \times 10^{-12} \text{ GeV}^{-3} \end{aligned}$$

(ii) BP2: $\Lambda = 730 \text{ GeV}$

$$\begin{aligned} |G_S^{e\mu}| &= 5.22 \times 10^{-11} \text{ GeV}^{-3}, \\ |G_P^{e\mu}| &= 1.46 \times 10^{-11} \text{ GeV}^{-3}, \\ |\tilde{G}_S^{e\mu}| &= 2.47 \times 10^{-11} \text{ GeV}^{-3}, \\ |\tilde{G}_P^{e\mu}| &= 5.96 \times 10^{-12} \text{ GeV}^{-3} \end{aligned}$$

(iii) BP3: $\Lambda = 1859 \text{ GeV}$

$$\begin{aligned} |G_S^{e\mu}| &= 2.70 \times 10^{-11} \text{ GeV}^{-3}, \\ |G_P^{e\mu}| &= 1.92 \times 10^{-11} \text{ GeV}^{-3}, \\ |\tilde{G}_S^{e\mu}| &= 3.26 \times 10^{-11} \text{ GeV}^{-3}, \\ |\tilde{G}_P^{e\mu}| &= 3.16 \times 10^{-11} \text{ GeV}^{-3} \end{aligned}$$

In addition to these values strictly satisfying stringent current experimental limits, the chosen cutoff scales ($\Lambda \sim 1\text{--}2 \text{ TeV}$) are phenomenologically motivated, as they are consistent with interpreting the reported excesses near 95, 150, and 650 GeV as new physics resonances [6,7]. If one estimates $M_{\phi_k} \sim C_{e\mu}^k |G_{e\mu}| \Lambda^4$ ($k = 1, 2, 3$) for our benchmarks, this connection requires coefficients $C_{e\mu}^k$ of $\mathcal{O}(1)$, suggesting a potential common UV origin that our cLFV search uniquely probes.¹

Collider analysis.

Signal and background:

- (i) Signal: We are interested in searching for the final state of an opposite-sign $e\mu$ pair, which is produced via UPCs ($\gamma\gamma \rightarrow e\mu$) in proton-proton (pp) collisions.
- (ii) Background: The dominant SM backgrounds are $qq \rightarrow W^-W^+$, $\gamma\gamma \rightarrow W^+W^-$, and $\gamma\gamma \rightarrow \tau^-\tau^+ \rightarrow e\mu + \nu's$, with smaller contributions from misidentified hadronic processes. To mitigate the substantial background from pileup, we employ the `delphes_card_HLLHC-Pile-up.tcl` ² configuration. Our simulation includes pileup with an average of 140 interactions per crossing, corresponding to HL-LHC conditions, via the `PileUpMerger` module and the `pileup`

¹Given that $|G_{e\mu}|$ has dimensions of GeV^{-3} , the mass M_{ϕ_k} has dimensions of GeV .

²This card is made available upon request.

TABLE I. Production cross sections of the signal for the three BPs. The number of events is evaluated for $\mathcal{L}_{\text{int}} = 3 \text{ ab}^{-1}$.

BPs	$\sigma(\gamma\gamma \rightarrow e\mu)$ (fb)	Events
BP1	0.04	120
BP2	0.035	105
BP3	0.013	39

TABLE II. Production cross sections of relevant SM background processes. The number of events is evaluated for $\mathcal{L}_{\text{int}} = 3 \text{ ab}^{-1}$.

Process	Cross section (fb)	Events
$\gamma\gamma \rightarrow WW \rightarrow e\nu_e\mu\nu_\mu$	0.623	1869
$\gamma\gamma \rightarrow \tau\tau \rightarrow e\nu_e\nu_\tau\mu\nu_\mu\nu_\tau$	28.2	84600
$qq \rightarrow WW \rightarrow e\nu_e\mu\nu_\mu$	890	2.67×10^6

per particle identification algorithm. The sensitivity could be further improved beyond our conservative estimates by using forward proton spectrometers (roman pots) to tag exclusive events and suppress pileup backgrounds [8,9].

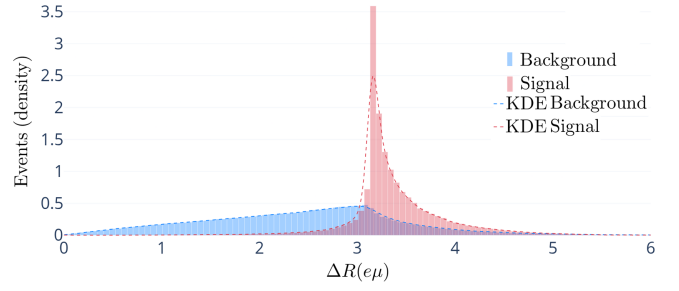
The numerical cross sections for the signal and dominant background processes are presented in Tables I and II, respectively. These results incorporate the fiducial cuts $p_T^{(e,\mu)} > 10 \text{ GeV}$, $|\eta^{(e,\mu)}| < 2.5$, and $\Delta R(e\mu) > 0.4$.

Signal and background events are generated with MadGraph5 (LanHEP/UFO) using the electric dipole form factor to model UPCs, showered with Pythia8 and passed through Delphes3 [10–16].

Multivariate analysis: The kinematic analysis revealed that the individual observables had relatively weak discriminating power to separate the signal from the background. To enhance the selection efficacy, we therefore employed a multivariate analysis (MVA) approach, which combined these observables into a single, more powerful discriminant. We use a boosted decision tree (BDT) method [17] based on the XGBoost library's gradient boosting implementation. The BDT classifiers were trained on a set of kinematic variables associated with the final-state objects, including the transverse momentum (p_T), pseudorapidity (η), angular separation (ΔR), transverse and invariant masses (M_T , M_{inv}), and azimuthal angle (ϕ).

The BDT selection is optimized to maximize the figure of merit, i.e., the signal significance, defined as $\mathcal{S} = N_S / \sqrt{N_S + N_B + (\kappa \cdot N_B)^2}$ [18], where N_S and N_B are the number of signal and background candidates, respectively. The factor $\kappa = 5\%$ stands for a realistic systematic uncertainty [19].

Building upon the previous MVA, the most powerful discriminating observables for distinguishing the signal from background processes are (i) the angular separation

FIG. 2. Angular separation $\Delta R(e\mu)$. We also include the fit kernel density estimation (KDE).

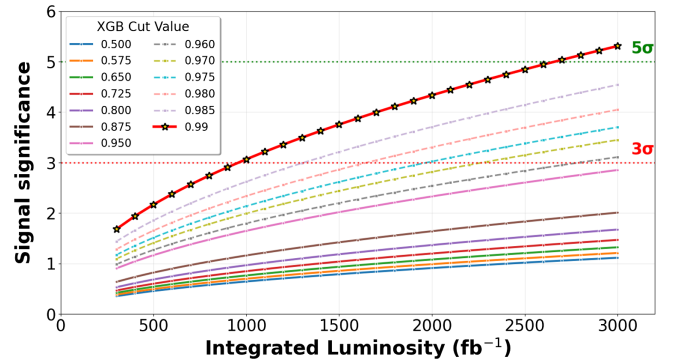
between the electron and muon $\Delta R(e\mu)$, (ii) the transverse mass of the electron $M_T(e) = \sqrt{2p_T^e E_T(1 - \cos \phi_{e\cancel{E}_T})}$, and (iii) the missing energy transverse $\cancel{E}_T$. The distribution of the most significant variable, which exhibits a pronounced separation between the signal and the several background channels, is presented in Fig. 2.

On the other hand, the absence of overtraining is confirmed by a Kolmogorov-Smirnov test, which yields high scores of 0.49 for the background and 0.34 for the signal.

The exceptional discovery potential of the signal at the HL-LHC is demonstrated by our key results in Fig. 3, which show the projected signal significance as a function of the integrated luminosity and the corresponding BDT classifier outputs for BP1.

The optimal scenario corresponds to BP1, and we obtain a signal significance of 5σ for $\mathcal{L}_{\text{int}} \gtrsim 2700 \text{ fb}^{-1}$ and a BDT cut of 0.99. Similar predictions are found for BP2, which predicts that a 5σ significance is achievable with $\mathcal{L}_{\text{int}} \gtrsim 2800 \text{ fb}^{-1}$. BP3 predicts up to approximately 2σ for an integrated luminosity of $\mathcal{L}_{\text{int}} \approx 3000 \text{ fb}^{-1}$.

Conclusions. We have shown the unique capability of the HL-LHC to probe charged lepton flavor violation through the ultraperipheral process $pp \rightarrow p(\gamma\gamma)p \rightarrow p(e^\pm\mu^\mp)p$. Our analysis, based on a dimension-seven effective field theory framework, reveals a direct connection between the

FIG. 3. Signal significance as a function of the integrated luminosity and the cut on the BDT prediction for BP1. Systematic uncertainties ($\kappa = 5\%$) are also considered.

experimental sensitivity and the underlying new physics scale Λ . Crucially, the benchmark points BP1 ($\Lambda = 1048$ GeV), BP2 ($\Lambda = 730$ GeV), and BP3 ($\Lambda = 1859$ GeV) span a phenomenologically meaningful range of cutoff scales. The fact that BP2—with the lowest allowed Λ —yields a strong signal highlights how this channel is particularly sensitive to new physics at the TeV scale. Meanwhile, BP3 demonstrates the challenge of probing higher scales, but still remains accessible at high luminosities. Notably, a 5σ discovery is achievable for $\Lambda \sim 1$ TeV with $\mathcal{L}_{\text{int}} \gtrsim 2700 \text{ fb}^{-1}$, while scales up to $\Lambda \sim 2$ TeV may be probed at the approximately 2σ level with $\mathcal{L}_{\text{int}} \approx 3000 \text{ fb}^{-1}$. This clear correlation between the cutoff scale and the required luminosity provides valuable guidance for future searches.

These results strongly motivate dedicated experimental efforts to search for $\gamma\gamma \rightarrow e\mu$ in early HL-LHC data. Future colliders with higher energy reach will be essential to extend this probe to even higher scales, offering a powerful tool to explore lepton flavor violation beyond the TeV frontier [20,21].

The high photon fluxes in Pb-Pb collisions offer a distinct advantage: They can substantially enhance the production cross section. This enhancement compensates for the lower

integrated luminosity, making it a highly promising channel. The net effect is an estimated increase in the number of observable events by approximately an order of magnitude compared to pp collisions [22,23].

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Data availability. The data that support the findings of this article are openly available [24].

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