

Lepton Flavor Violation and Dilepton Tails at the LHC

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Charged Lepton Flavor Violation (LFV) is a very clean probe of New Physics since it is forbidden in the Standard Model (SM). The observation of neutrino oscillation implies nonzero LFV rates, which however are highly suppressed by the smallness of neutrino masses. This makes LFV an appealing target of experimental searches, as its observation would unambiguously point to New Physics. In this proceedings, we will discuss the constraints on LFV effective operators that can be derived from LHC data on dilepton production. We will show that semileptonic operators can be constrained by existing searches of $pp \rightarrow \ell_i \ell_j$ (with $i \neq j$) at high- p_T . We will explore the complementarity of these constraints with the ones obtained from low-energy observables, by showing, in particular, that LHC data provides the best constraints for several quark-flavor conserving effective coefficients, as well as for the ones that are relevant for charm physics.

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1. Introduction

The Standard Model (SM) Lagrangian has an accidental symmetry $U(1)_e \times U(1)_\mu \times U(1)_\tau$, which guarantees the conservation of individual lepton flavor numbers and which must be broken since neutrinos are massive and oscillate. However, the smallness of neutrino masses ensures that all decays with Lepton Flavor Violation (LFV) are highly suppressed and thus not observable, in the absence of further contributions beyond the SM. For this reason, these processes are very clean probes of New Physics effects.

Several extensions of the SM predict potentially large effects in LFV processes, see e.g. Ref. [1] for a review. These effects can appear in purely leptonic decays, such as $\ell_i^- \rightarrow \ell_j^- \gamma$ and $\ell_i^- \rightarrow \ell_j^- \ell_k^+ \ell_k^-$, with $i > j \geq k$, which are the target of several ongoing and future experiments in the lepton sector [2]. LFV in semileptonic transitions $q_i \rightarrow q_j \ell_k^+ \ell_l^-$ are also compelling probes of New Physics. These effects would be predominant, for instance, in scenarios with leptoquark states or new Z' bosons, as they could induce these effects already at tree-level, see e.g. Ref. [3]. Presently, there is a rich experimental program dedicated to these processes at NA62 [4], BES-III [5], and LHCb [6] and Belle-II [7], which will greatly improve the experimental sensitivity on LFV decays of K -, D - and B -mesons in the coming years.

LHC searches also offer new possibilities to constrain flavor physics at high- p_T [8, 9]. The main idea here is to exploit the energy-enhancement of the dilepton-production cross-section in the presence of higher-dimension operators. Complementary constraints to low-energy probes can be derived in these studies, as explored e.g. in the context of the discrepancies observed in B -meson decays [10]. In this proceedings, we discuss the limits on semileptonic LFV operators that can be derived by using LHC bounds on the high- p_T tails of the processes $pp \rightarrow \ell_k \ell_l$ with $k \neq l$ [11].

2. EFT description

First, we define our Effective Field Theory (EFT) and provide general expressions for $\sigma(pp \rightarrow \ell_k^\pm \ell_l^\mp)$ within this framework. We consider the following effective Lagrangian,

$$\mathcal{L}_{\text{eff}} \supset \sum_{\alpha} \sum_{ijkl} \frac{C_{\alpha}^{ijkl}}{v^2} O_{\alpha}^{ijkl}, \quad (1)$$

where $v = (\sqrt{2}G_f)^{-1/2}$ is the electroweak vacuum expectation value, O_{α}^{ijkl} are the semi-leptonic operators listed in Table 1 and C_{α}^{ijkl} are effective coefficients. In our notation, $q_{i,j}$ can denote either up or down-type quarks. The matching of Eq. (1) to the SM EFT is provided in Ref. [11]. By neglecting the fermion masses, we can generically express the differential partonic cross-section for this process as follows

$$\left[\frac{d\hat{\sigma}}{d\hat{t}} \right]_{ijkl} = \frac{1}{48\pi v^4 \hat{s}^2} \left\{ \hat{t}^2 \left[|C_{V_{LR}}|^2 + |C_{V_{RL}}|^2 \right] + (\hat{s} + \hat{t})^2 \left[|C_{V_{LL}}|^2 + |C_{V_{RR}}|^2 \right] \right. \\ \left. + \frac{\hat{s}^2}{4} \left[|C_{S_L}|^2 + |C_{S_R}|^2 \right] + 4(\hat{s} + 2\hat{t})^2 |C_T|^2 - 2\hat{s}(\hat{s} + 2\hat{t}) \text{Re}(C_{S_L} C_T^*) \right\},$$

Eff. coeff.	Operator	SMEFT
$C_{V_{LL}}^{ijkl}$	$(\bar{q}_{Li}\gamma_{\mu}q_{Lj})(\bar{\ell}_{Lk}\gamma^{\mu}\ell_{Li})$	$O_{lq}^{(1)}, O_{lq}^{(3)}$
$C_{V_{RR}}^{ijkl}$	$(\bar{q}_{Ri}\gamma_{\mu}q_{Rj})(\bar{\ell}_{Rk}\gamma^{\mu}\ell_{Rl})$	O_{ed}, O_{eu}
$C_{V_{LR}}^{ijkl}$	$(\bar{q}_{Li}\gamma_{\mu}q_{Lj})(\bar{\ell}_{Rk}\gamma^{\mu}\ell_{Rl})$	O_{qe}
$C_{V_{RL}}^{ijkl}$	$(\bar{q}_{Ri}\gamma_{\mu}q_{Rj})(\bar{\ell}_{Lk}\gamma^{\mu}\ell_{Li})$	O_{lu}, O_{ld}
$C_{S_R}^{ijkl}$	$(\bar{q}_{Ri}q_{Lj})(\bar{\ell}_{Lk}\ell_{Rl}) + \text{h.c.}$	O_{ledq}
$C_{S_L}^{ijkl}$	$(\bar{q}_{Li}q_{Rj})(\bar{\ell}_{Lk}\ell_{Rl}) + \text{h.c.}$	$O_{lequ}^{(1)}$
C_T^{ijkl}	$(\bar{q}_{Li}\sigma_{\mu\nu}q_{Rj})(\bar{\ell}_{Lk}\sigma^{\mu\nu}\ell_{Rl}) + \text{h.c.}$	$O_{lequ}^{(3)}$

Table 1: Operators O_{α} appearing in Eq. (1) and their corresponding operators in the SM EFT (third column). Flavor indices are denoted by i, j, k, l , and q stands for either up or down-type quarks in the mass basis. Wilson coefficients are assumed to be real. See the Appendix of Ref. [11] for details.

where \hat{s} denotes the partonic energy and $\hat{t} \in (-\hat{s}, 0)$. After integration over \hat{t} , we obtain

$$[\hat{\sigma}(\hat{s})]_{ijkl} = \frac{\hat{s}}{144\pi v^4} \sum_{\alpha\beta} C_{\alpha} C_{\beta}^* M_{\alpha\beta}, \quad (2)$$

where $\alpha, \beta \in \{V_{LL}, V_{RR}, V_{LR}, V_{RL}, S_L, S_R, T\}$ and $M_{\alpha\beta}$ is a matrix of numeric coefficients. In this equation, one should perform the following replacements

$$C_{V_{X,Y}} \rightarrow C_{V_{X,Y}}^{ijkl}, \quad C_{S_X} \rightarrow \sqrt{|C_{S_X}^{ijkl}|^2 + |C_{S_X}^{jilk}|^2}, \quad C_T \rightarrow \sqrt{|C_T^{ijkl}|^2 + |C_T^{jilk}|^2}, \quad (3)$$

where $X, Y \in \{L, R\}$, and M is a diagonal matrix $M_{\alpha\beta} \equiv \delta_{\alpha\beta} M_{\alpha}$, with $M = (1, 1, 1, 1, 3/4, 3/4, 4)$. The partonic cross-section should be convoluted with the relevant parton-parton luminosities [12], which in this work we define by the dimensionless functions

$$\mathcal{L}_{q_i\bar{q}_j}(\tau) = \tau \int_{\tau}^1 \frac{dx}{x} [f_{q_i}(x, \mu_F) f_{\bar{q}_j}(\tau/x, \mu_F) + (q_i \leftrightarrow \bar{q}_j)], \quad (4)$$

where f_{q_i} denotes the quark q_i parton distribution functions (PDF), μ_F is the factorization scale and \sqrt{s} stands for the proton-proton center-of-mass energy, with $\tau = \hat{s}/s$. In our analysis, we consider the PDF4LHC15_nnlo_mc PDF set [13–16] and included the 1σ PDF uncertainties derived by using the MC replica method [17]. The hadronic cross-section is then given by the expression

$$\sigma(pp \rightarrow \ell_k^- \ell_l^+) = \sum_{ij} \int \frac{d\tau}{\tau} \mathcal{L}_{q_i\bar{q}_j}(\tau) [\hat{\sigma}(\tau s)]_{ijkl}, \quad (5)$$

where the summation extends over all quark flavors, with the exception of the top quark which only contributes at one-loop to this process [18]. Note that if the partonic cross-section $\hat{\sigma}$ is a linear function in τ , as it is our case, then the only dependence on τ of the integrand in Eq. (5) comes from the luminosity functions defined in Eq. (4).

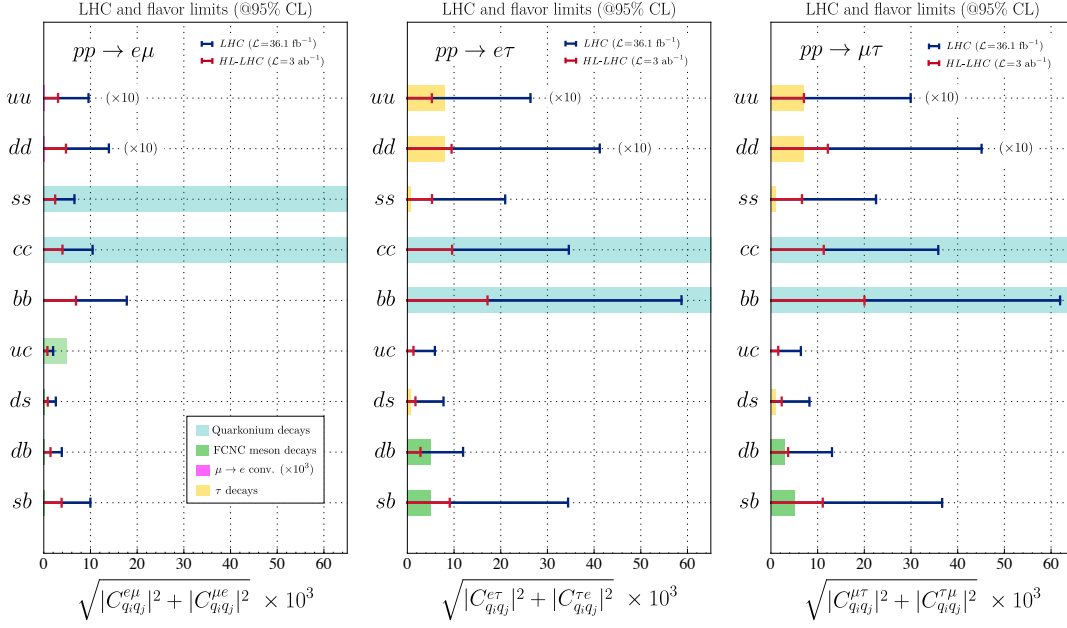


Figure 1: Limits derived from high- p_T LFV dilepton tails on the coefficients $\sqrt{|C_{q_i q_j}^{\ell_k \ell_l}|^2 + |C_{q_i q_j}^{\ell_l \ell_k}|^2}$ by using 13 TeV ATLAS searches into the $e\mu$ channel (left panel), the $e\tau$ channel (middle panel) and the $\mu\tau$ channel (right panel)s [19]. For comparison, we also show the limits obtained by the flavor physics observables, namely quarkonium decays (cyan), $\mu N \rightarrow eN$ (magenta), FCNC meson decays (green) and LFV τ -decays (yellow). LHC and flavor results for $uu, dd \rightarrow e\mu, e\tau, \mu\tau$ have been rescaled by an additional factor of $\times 10$ for visibility. The limits from $\mu N \rightarrow eN$ have been rescaled by a factor of $\times 10^3$ to become visible.

3. Recast of high- p_T results

We considered the latest ATLAS search for heavy vector resonances decaying into leptons with different flavors, $pp \rightarrow Z' \rightarrow \ell_k^\pm \ell_l^\mp$, performed at $\sqrt{s} = 13$ TeV with 36.1 fb^{-1} of data [19]. This search was recast for the final states $e\mu$, $e\tau$ and $\mu\tau$, following the procedure described in Ref. [11]. The bins of dilepton invariant mass $m_{\ell_k \ell_l}$ above 300 GeV have been combined to extract 95% confidence level (CL) upper limits on the effective coefficients defined in Eq. (1) for all possible quark-flavor combinations. Projections for the High-Luminosity LHC phase (HL-LHC) for a luminosity of 3 ab^{-1} have been obtained by assuming that the data scales naively with the luminosity ratio and that all uncertainties scale with the square-root of the luminosity ratio. Our results are reported in Fig. 1 for the benchmark scenario defined by $C_{q_i q_j}^{\ell_k \ell_l} \equiv C_{V_{LL}}^{ijkl}$, where i, j are flavor indices of down (d, s, b) or up-type quarks (u, c), and k, l of charged leptons (e, μ, τ), in the mass basis. Our definition is such that Hermiticity of Eq. (1) implies $C_{q_i q_j}^{\ell_k \ell_l} = (C_{q_j q_i}^{\ell_l \ell_k})^*$.

4. Discussion

In Fig. 1, we compare the constraints we have derived from high- p_T LHC data with the ones extracted from searches for low-energy LFV observables that depend, at tree-level, on the same effective couplings $C_{q_i q_j}^{\ell_k \ell_l}$. There are several types of low-energy observables that are relevant for our analysis [20]: (i) processes that also violate quark flavor, such as $K \rightarrow \pi \mu e$, $B_s \rightarrow \ell_k \ell_l$ and

$B \rightarrow K^{(*)} \ell_k \ell_l$; (ii) quarkonia decays, such as $J/\psi \rightarrow \ell_k \ell_l$ and $\Upsilon \rightarrow \ell_k \ell_l$; (iii) τ -decays, such as $\tau \rightarrow \mu \phi$ and $\tau \rightarrow \mu \pi$; and (iv) $\mu \rightarrow e$ conversion in nuclei. Several conclusions can be derived from Fig. 1:

- We find that high- p_T constraints are significantly better than low-energy observables for quark-flavor conserving coefficients such as C_{cc}^{lk} and C_{bb}^{lk} , for all lepton flavors. The same conclusion also holds for $C_{ss}^{e\mu}$. This is the case because the low-energy observables that can probe these coefficients are quarkonia decays (ϕ , J/ψ and Υ), which are highly suppressed by the large quarkonia decay width since these particles are flavor singlets.
- Our high- p_T results are the only available constraints for the transitions $c \rightarrow ue\tau$ and $c \rightarrow u\mu\tau$, since there are no kinematically allowed flavor processes that can probe these transitions in exclusive meson decays.
- For quark-flavor violating processes, such as kaon and $B_{(s)}$ -meson LFV decays, flavor limits are in general much more constraining than our high- p_T limits. The only exceptions are the $b \rightarrow de\tau$ and $b \rightarrow d\mu\tau$ transitions, for which the HL-LHC projections are comparable to the current sensitivity on the decays $B \rightarrow \pi e \mu$ and $B \rightarrow \pi \tau \mu$, as well as on the related leptonic modes [20].

In conclusion, there is a striking complementarity between the LFV limits that can be extracted from low-energy searches and from the study of high- p_T tails, as explored in Ref. [11]. Same conclusions have also been obtained for flavor-conserving transitions, which can be constrained by the high- p_T tails of $pp \rightarrow \ell\ell$ [8] and $pp \rightarrow \ell\bar{\nu}$ [9]. This complementarity was highlighted in this proceedings for left-handed operators, but it also holds to a smaller extent for scalar and tensor operators. These results illustrate that the combination of indirect low and high-energy searches is of fundamental importance in order to efficiently probe New Physics scenarios in the flavor sector.

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