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Connecting low- and high-energy observables at future colliders

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Establishing the physics potential of future colliders is one of the main objectives of the HEP community in the coming years. The aim is on the one hand to consolidate the physics expectations from a circular collider working between the Z-pole and the $t\bar{t}$-threshold (FCC-ee at CERN) and exploring completely new avenues and technologies such as a multi-TeV e^+e^- or even $\mu^+\mu^-$ collider. In light of that, this work aims at connecting the potentialities of low-energy experiments (e.g. the muon $g-2$ experiment at Fermilab, Belle II at KEK, MEG-II at PSI) with the possibilities that will open at precision e+ e- colliders. The main point is to access information on the SM which is currently out of reach. In particular, an initial study is aimed at the phenomenology of Lepton Flavor Violation (LFV) where we have investigated the reaches of low-energy experiments as well as high-energy experiments (like the HL-LHC and future colliders). Assuming heavy new physics, the study of LFV effects is based on tools and techniques of effective field theories. In particular, we evaluated the decay rates for several LFV processes as well as the cross sections for the LFV high-energy scatterings in the Standard Model Effective Field Theory (SMEFT). In addition, we placed bounds on the fundamental parameters of the NP framework, showing that new infrastructure can better constrain the parameter space than low-energy experiments, specifically for observables related to τ production.

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1. Charged Lepton Flavor Violation and the Standard Model

The Standard Model (SM) [1] is the leading modern theory regarding the physics of the fundamental interactions. However, despite its huge successes, it is far from being a perfect theory due to various issues [2]. The experimental motivations to expect new physics, like the neutrino oscillations or the matter-antimatter asymmetry, are clear evidence of our lack of understanding and require advancements in precision measurements. On the theoretical side, puzzles such as the hierarchy problem or the strong CP problem leave fundamental questions unsolved and present features that suggest SM might be part of a broader theory. In search of solutions, new physics scenarios have been proposed over the years predicting new particles extending the SM. The possibility of heavy new physics well above the electroweak scale is further supported by the absence of new signals at the LHC. Establishing the physics potentialities of future colliders is then one of the main objectives of the HEP community in the coming years. The high energy, intensity and precision of the new machines may offer a sizeable improvements for the sensitivity to small deviations from the SM. As an example, the first stage [3] of the Future Circular Collider (FCC-ee) could be able to probe processes between the Z-pole and the $t\bar{t}$-threshold acting as a Higgs and electroweak factory. Another proposed project is a muon collider [4] that could operate using less energy than other types of accelerators due to the small synchrotron radiation of muons. Focusing on the phenomenology, an attracting avenue to look for new physics is the possible violation of the lepton flavor, expected to be broken at higher energies [5, 6]. This is well motivated by the observation of neutrino oscillations, which opens the possibility of mixing phenomena between charged leptons. In the SM, Charged Lepton Flavor Violating (CLFV) processes are predicted to occur at the loop level via the virtual exchange of electroweak bosons and massive neutrinos. However, as a consequence of the GIM mechanism, the predicted rates are so small that are basically unobservable with current experimental techniques. Therefore the observation of CLFV would be an clear sign of new physics. Already at low energies efforts have been made to study rare decays, such as $\mu \to e\gamma$, $\tau \to 3e$ or $\mu - e$ conversion in nuclei. The current CLFV bounds [7] point towards a high new physics scale $\Lambda \gg M_W$.

2. Standard Model Effective Field Theory

Assuming the existence of heavy new degrees of freedom, effective field theories allow us to parametrize the effects of new physics in a model independent way. In a bottom-up approach, the Standard Model Effective Field Theory (SMEFT) [8, 9] is constructed adding to the SM Lagrangian an infinite tower of higher dimensional operators built with the SM fields and respecting the gauge symmetry. The series is organized using proper power counting to determine which terms should be retained at a given perturbative order. This counting method is based on the suppression provided by the new physics scale ($\Lambda \gg M_W$) to arrange the effective interactions as a series of higher dimensional operators. At dimension-5 only one operator is allowed, the Weinberg operator, which violates the lepton number, beyond the scope of this work. The first important new operators arise at dimension-6 and describe new physics phenomena. However, dealing with CLFV, our attention is focused on the three main subclasses shown in Tab.(1).

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Four-fermion operators	
$O_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$
O_{ee}	$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$
$O_{\ell e}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$
Dipole operators	
O_{eW}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_a\Phi W^a_{\mu\nu}$
O_{eB}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$
Fermion-Higgs operators	
$O^{(1)}_{\Phi\ell}$	$(\Phi^\dagger iD_\mu\Phi)(\bar{L}_L\gamma^\mu L_L)$
$O^{(3)}_{\Phi\ell}$	$(\Phi^\dagger iD^a_\mu\Phi)(\bar{L}_L\tau_a\gamma^\mu L_L)$
$O^{(1)}_{\Phi e}$	$(\Phi^\dagger iD_\mu\Phi)(\bar{e}_R\gamma^\mu e_R)$
$O_{e\Phi}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

Table 1: SMEFT operators contributing to CLFV processes.

The crucial feature of SMEFT is the possibility to combine limits coming from different processes. The Wilson coefficients indeed could be active in different scenarios, whose current experimental limits might better constrain the parameter space. At low energy exotic phenomena such as $\tau \to 3\mu$ might happen, while in future colliders flavor violating lepton collisions could be searched for.

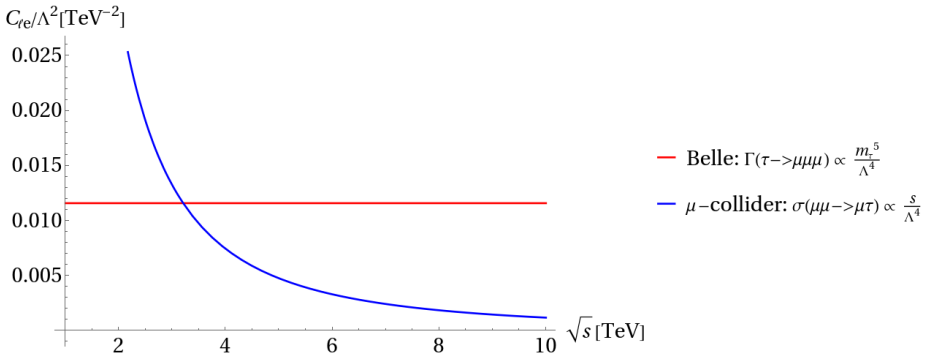

Figure 1: Upper bounds for the Wilson coefficient $C_{\ell e}/\Lambda^2$ studying the low-energy process $\tau \to 3\mu$ at Belle versus the CLFV prediction of $\mu\mu \to \tau\mu$ at muon collider.

A key point is the amplification of the new physics signal regarding high-energy observables. In fact, while the flavor violating decay rates are energetically constrained by the mass of the decaying particle, the cross sections grow with the energy. In Fig.(1) are shown the upper bounds for $C_{\ell e}/\Lambda^2$ coming from Belle experiment and the prediction for a muon collider. It is evident that observing the production of LFV pairs can scan over a large range of the Wilson's coefficients. In other words, starting from a few TeV the parametric enhancement, typical of the effective theories, improves our sensitivity on CLFV. We could then exploit this boost to improve the current limits related to the τ production, which are less precise with respect to the production of lighter leptons. As an initial study, my attention focused in the process $e^+e^- \to e\tau$, described at tree-level by the diagrams in Fig. (2). The low-energy competitors, given by the diagrams in Fig. (3), are the decay $\tau \to 3e$ and the flavor violating decays of the Z and Higgs bosons.

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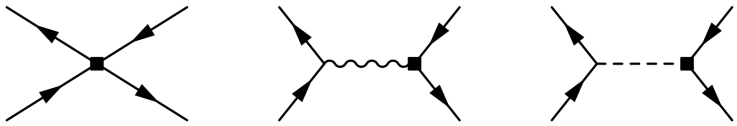

Figure 2: Tree-level Feynman diagrams contributing to the process ee $\to \tau$e (plus t-channel)

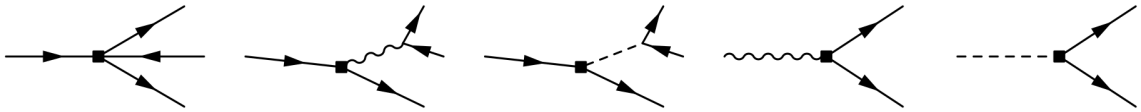

Figure 3: Tree-level Feynman diagrams describing the decays $\tau \to 3e$ and $Z, h \to \tau e$.

3. Exclusion Bounds at Future Colliders

Analyzing the sensitivity of future colliders at 95%C.L. corresponds to impose

$$N_s \geqslant 2\sqrt{N_b + N_s}\,, \tag{1}$$

where N_s and N_b are understood as the number of signal and background events. It is well known that signal and cross sections are related to each other through the integrated luminosity L and the efficiency ϵ of the detector via

$$N_s = \epsilon \mathcal{L} \sigma\,. \tag{2}$$

Regarding the background events N_b , the analysis has been carried out following [10, 11]. In a nutshell, at the energy of the FCC-ee SM processes may mimick the product of the reaction. Especially near the Z-pole the high number of Z bosons produced in s-channels is the principal sources of SM background, which must be filtered out. The main ones are the following:

- $\mathrm{e^+e^-} \to \mathrm{Z^*}/\gamma^* \to \tau^+\tau^- \to \tau_{\mathrm{had.}}\mathrm{e^+}\nu_\mathrm{e}\overline{\nu}_\tau$,
- $\mathrm{e^+e^-} \to \mathrm{W^*W^*}/\mathrm{Z^*Z^*} \to \tau_{\mathrm{had.}}\mathrm{e^+}\nu_\mathrm{e}\overline{\nu}_\tau$.

A simple way to select the signal over the background [11] is by filtering the momentum of the outgoing electron, requiring that

$$\frac{p_e}{p_{\mathrm{beam}}} \gtrsim 1\,, \tag{3}$$

naming p_e and p_{beam} the absolute values of the electron and beam momenta.
That being said, the interplay of low-energy experiments with the predictions of future colliders is shown in the contour plots of Fig.(4), having two operators switched on at the same time. On the right the restriction is between a Z dipole operator and a Higgs-lepton one, while on the left the competition concerns only four-fermion operators but with different chiralities. The upper limits obtained by Belle II and OPAL/ATLAS are reported in [6, 12]. Even near the electroweak scale, a new collider like the FCC-ee could improve the bounds on τ production by the Z boson compared to low-energy measurements. The resulting parametric enhancement of high-energy observables help us to exclude smaller regions in the parameter space. In contrast, the energy reach is not enough to match the future projections of Belle II dealing with four-fermion operators.

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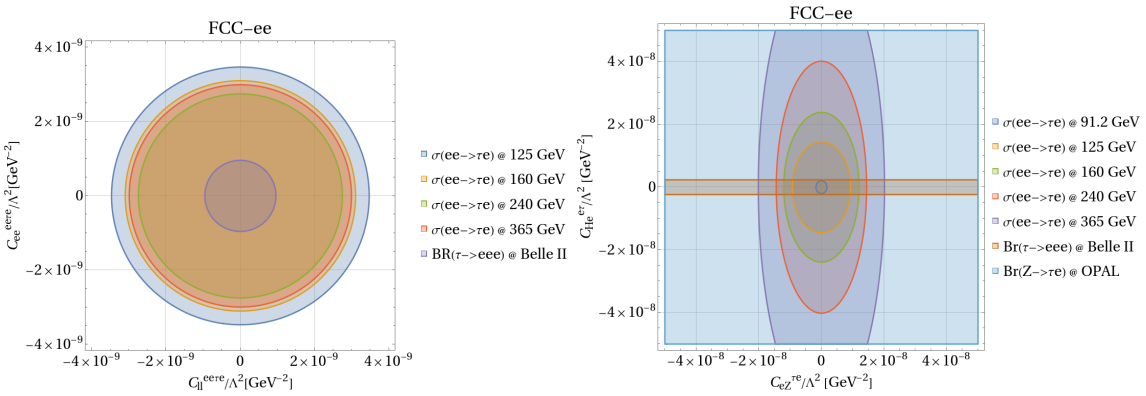

Figure 4: Exclusion regions in the parameters space of the Wilson coefficients $C_{\ell\ell}^{ee\tau e}$ vs $C_{ee}^{ee\tau e}$ (left) and $C_{eZ}^{\tau e}$ vs $C_{He}^{e\tau}$ (right) showing the FCC-ee projections.

The searches have been extended studying also similar processes in the case of a muon collider. In Fig.(5) are reported the exclusion regions obtained by the scattering of muons into a lepton violating pair, such as $\mu\mu \to \tau e$. On the left the restriction is between a four-fermion operators of different chiralities, while on the right the active operators are a Z dipole operator and a Higgs-lepton one. As a result, this second machine is able to exploit well the parametric enhancement provided by quadratic energy scaling of the cross sections generated by contact interactions.

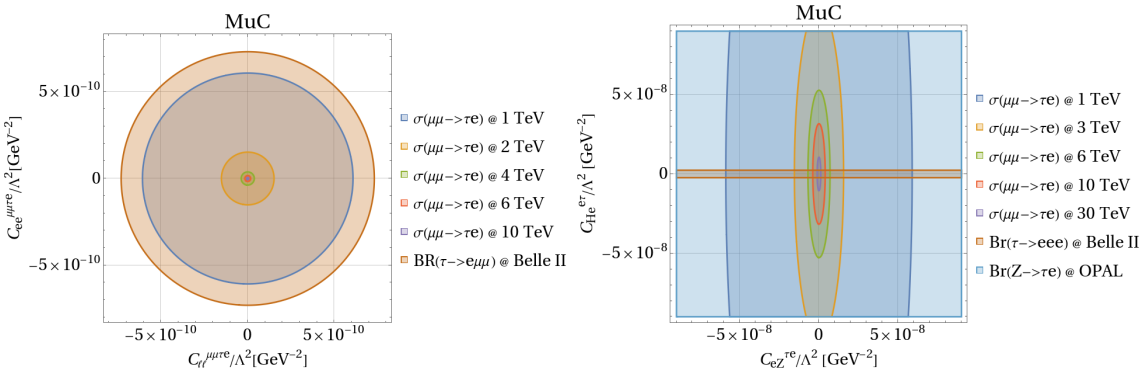

Figure 5: Exclusion regions in the parameters space of the Wilson coefficients $C_{\ell\ell}^{\mu\mu\tau e}$ vs $C_{ee}^{\mu\mu\tau e}$ (left) and $C_{eZ}^{\tau e}$ vs $C_{He}^{e\tau}$ (right) showing the muon collider projections.

4. Conclusion

In conclusion, the extreme suppression of flavor violation in the SM makes every possible observation of CLFV the smoking gun of new physics. SMEFT offers an excellent model-independent approach in which the Wilson coefficients can be constrained combining results of different measurements. For this reason, the interplay between low- and high-energy experiments is crucial to analyze the potentialities of future colliders and to place relevant bounds on the coefficients of the new physics.

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