Charged Lepton Flavor Violation in Electron-Positron Collisions

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Abstract

In the Standard Model, lepton-flavor violating processes such as $e^+e^- \to \tau^+e^-$ are forbidden; however, many New Physics (NP) models allow charged lepton flavor violation [4][5]. The goal of this project is to derive model-independent constraints on the coupling constants of lepton-flavor violating operators from the scattering cross section and left-right asymmetry measured in e^+e^- experiments.

1 Introduction

The discovery of neutrino oscillations indicated that lepton flavor violation does indeed take place; however, charged lepton flavor violation (involving electrons, muon, taus, and their antiparticles) has not been observed. This is consistent with the Standard Model since Standard Model contributions to charged lepton flavor violation (CLFV) is heavily suppressed by the tiny neutrino masses to levels beyond current detector sensitivity [3] [8]. Thus, any observation of CLFV would be an unambiguous indicator of physics beyond the Standard Model. Experiments have not been able to detect CLFV; as a result, upper bounds constraint the prevalence of CLFV.

Since lepton flavor is conserved in the Standard Model, it is convenient to normalize the CLFV cross section that we are about to compute to similar Standard Model cross sections (e.g. the ratio $\sigma(ee \to e\tau)/\sigma(ee \to \tau\tau)$). For that, we turn to a classic calculation in quantum electrodynamics

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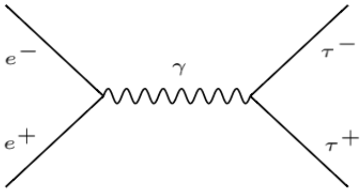
(QED): $e^+e^- \to \tau^+\tau^-$. Here, we consider only the tree-level Feynman diagram,

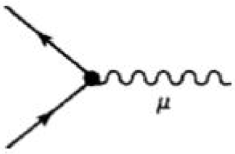


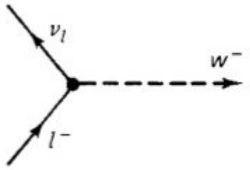
The machinery of QED predicts that the tree-level scattering cross section is approximately $\sigma = \frac{4\pi\alpha^2(\hbar c)^2}{3s}$, where $\alpha = e^2/(4\pi)$ is the electromagnetic fine structure constant, e is the elementary charge and $\sqrt{s}$ is the total center-of-mass energy. The coupling constant α originates from the interaction term of the QED Lagrangian:

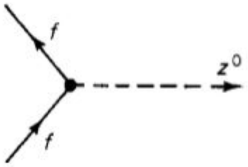
$$\mathcal{L}_{int} = e(\bar{\psi}\gamma^\mu\psi)A_\mu \tag{1}$$

Here, γ_μ is the Dirac matrix, ψ represents the electron field, and A_μ represents the photon field. We can see that the scattering cross section σ is proportionate to the coupling constant α. In other words, the value of the coupling constant determines the strength of the interaction.

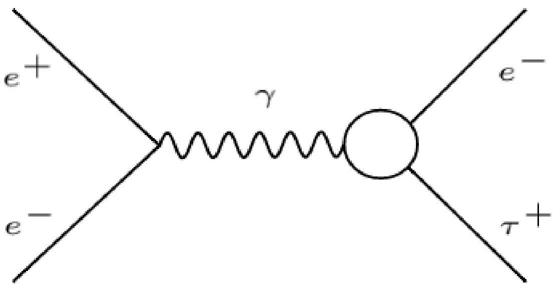
Using the Lagrangian of QED Eq. (1) and a Lagrangian for the electroweak theory, one can derive a set of Feynman rules for the lepton vertices [6]:



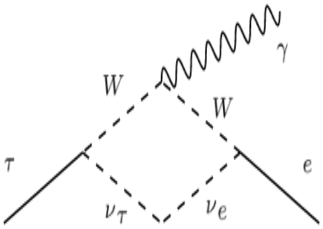




With these three vertices, it is impossible to construct a Feynman diagram for lepton-flavor-violating processes such as $e^+e^- \to \tau^+e^-$. Therefore, CLFV must be mediated by some Beyond Standard Model vertex whose structure we do not know:



One possibility for this new vertex is neutrino oscillation facilitating flavor violation, where the neutrino conversion $\nu_\tau \to \nu_e$ is proportionate to $U_{\tau e}$, an element of the flavor-mixing PMNS matrix [6].



While this diagram is part of the Standard Model with massive neutrinos, the contribution is heavily suppressed by the tiny neutrino masses – the Standard Model predicts $\mathcal{B}(\mu \to e\gamma) \sim 10^{-54}$ [3]. There are many models that give much larger contributions by incorporating physics beyond the Standard Model. Using effective field theory, we can make calculations without committing to a particular model.

In our research, we used the Mathematica package FeynCalc to perform Feynman diagram calculations [7, 9].

2 Effective Field Theory

Surprisingly, without knowing the exact structure of the flavor-violating vertex, the scattering cross section can still be calculated. Results from Effective Field Theory state that any New Physics model corresponds to a set of six coupling values, separating left-chiral and right-chiral contributions as well as discriminating between non-photon and photon contributions [4]. As a result, the effective Hamiltonian has six terms:

$$H_{eff} = H_{lept}^{(LL)(LL)} + H_{lept}^{(RR)(RR)} + H_{lept}^{(LL)(RR)} + H_{lept}^{(RR)(LL)} + H_{rad}^{(LR)} + H_{rad}^{(RL)} \tag{2}$$

The first four terms are strictly leptonic and do not involve photon mediators [4]. Note that the vertex operator is γ_μ, same as in the QED interaction term:

$$H_{lept}^{(LL)(LL)} = \frac{g_V^{(LL)(LL)}}{\Lambda^2}(\bar{l}_L\gamma_\mu\tau_L)(\bar{l}_L\gamma^\mu l_L) \tag{3}$$

$$H_{lept}^{(RR)(RR)} = \frac{g_V^{(RR)(RR)}}{\Lambda^2}(\bar{l}_R\gamma_\mu\tau_R)(\bar{l}_R\gamma^\mu l_R) \tag{4}$$

$$H_{lept}^{(LL)(RR)} = \frac{g_V^{(LL)(RR)}}{\Lambda^2}(\bar{l}_L\gamma_\mu\tau_L)(\bar{l}_R\gamma^\mu l_R) \tag{5}$$

$$H_{lept}^{(RR)(LL)} = \frac{g_V^{(RR)(LL)}}{\Lambda^2}(\bar{l}_R\gamma_\mu\tau_R)(\bar{l}_L\gamma^\mu l_L) \tag{6}$$

The last two terms come from radiative operators, contributing to the amplitude by a photon mediator:

$$\begin{aligned}
H_{rad}^{(LR)} &= -\frac{q}{8\pi}\frac{v}{\Lambda^2}g_{rad}^{(LR)}(\bar{l}_L\sigma_{\mu\nu}\tau_R)F^{\mu\nu} \\
H_{rad}^{(RL)} &= -\frac{q}{8\pi}\frac{v}{\Lambda^2}g_{rad}^{(RL)}(\bar{l}_R\sigma_{\mu\nu}\tau_L)F^{\mu\nu} \\
\sigma_{\mu\nu} &= \frac{i}{2}(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)
\end{aligned}$$

The g constants are six unknown coupling constants we wish to probe with electron-positron colliders. The high energy scale Λ suppresses CLFV at low energies. Other constants are e the elementary charge, and v the Higgs coupling constant. Although the values of the coupling constants have not been measured, upper bounds can be derived from the constraints placed by experiments.

3 Constraints Placed by Experiments

Charged lepton flavor violation has not been observed by experiments, likely due to the sensitivity level of the detectors. Instead, experiments have placed constraints on the likelihood of CLFV. The BaBar collaboration at SLAC, operating at $\sqrt{s} = 10.58$ GeV, placed an upper bound on $ee \to \tau e$ in July 2006 [2]:

$$\sigma(e\ e \to e\ \tau) < 9.2 \text{ fb}. \tag{7}$$

More recently in February 2015, the LHCb collaboration at CERN, operating at both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, placed a constraint on the branching ratio of τ^- decay [1]:

$$BR(\tau^- \to \mu^-\mu^+\mu^-) < 4.6 \times 10^{-8}. \tag{8}$$

4 CLFV Calculation

We have successfully derived the total cross section of $e^+e^- \to \tau^+e^-$ for the first four terms (the H_{lept} terms):

$$\sigma_{lept} = \frac{(m_\tau^2 - s)^2(m_\tau^2 + 2s)(g_V^{(LL)(LL)^2} + g_V^{(LL)(RR)^2} + g_V^{(RR)(LL)^2} + g_V^{(RR)(RR)^2})}{96\pi\Lambda^4 s^2} \tag{9}$$

What follows is a simple phenomenology calculation. Using the aforementioned BaBar constraint at $\sqrt{s} = 10.58$ GeV (Equation 7), and substituting $m_\tau = 1.777\ GeV/c^2$, we have:

$$\frac{(g_V^{(LL)(LL)^2} + g_V^{(LL)(RR)^2} + g_V^{(RR)(LL)^2} + g_V^{(RR)(RR)^2})}{(\Lambda/GeV)^4} < 3.3 \times 10^{-11} \tag{10}$$

Furthermore, since the constraint is on the sum of different contributions, we can obtain a constraint on specific contributions by assuming that one operator dominates, e.g. $g_V^{(LL)(LL)}$:

$$\frac{g_V^{(LL)(LL)}}{(\Lambda/GeV)^2} < 5.8 \times 10^{-6} \tag{11}$$

Note that the energy scale Λ (taken in units of GeV) is indeed much greater than the g coupling constants.

We have also calculated the cross section for all six operators; however, the expression is too lengthy to show in its entirety, so we present the result of the phenomenology calculation for the constraint:

$$\frac{1}{(\Lambda/GeV)^4}\Big((g_V^{(LL)(LL)^2} + g_V^{(LL)(RR)^2} + g_V^{(RR)(LL)^2} + g_V^{(RR)(RR)^2}) \\ -8.433 \times 10^{-2}(g_V^{(LL)(RR)} g_{rad}^{(LR)} + g_V^{(RR)(LL)} g_{rad}^{(RL)}) + 4.509(g_{rad}^{(LR)^2} + g_{rad}^{(RL)^2})\Big) < 3.3 \times 10^{-11} \tag{12}$$

Assuming single operator dominance on $g_{rad}^{(LR)}$, we obtain a more specific constraint:

$$\frac{g_{rad}^{(LR)}}{(\Lambda/GeV)^2} < 2.7 \times 10^{-6} \tag{13}$$

5 Summary

Charged lepton flavor violation is allowed by many New Physics models. We have derived an expression for the scattering cross section of eletron antitau production ($e^+e^- \to \tau^+e^-$) as a function of six coupling constants and total center-of-mass energy. The next step is to account for spin polarization in order to calculate asymmetry. After that, higher-order Feynman diagrams will be considered. Experiments such as BES III and Belle II will be able to probe CLFV using the method proposed here.

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