Lepton Flavor Changing Neutral Current Processes at Lepton-Hadron Colliders

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Abstract

We investigate the potentials of high energy lepton-proton colliders to detect a flavor changing \(l - l' - Z\) or \(l - l' - \gamma\) couplings from the processes \(ep \rightarrow \mu(\tau)X\) and \(\mu p \rightarrow \tau X\). For the \(l - l' - Z\) coupling we consider string inspired \(E_6\) model whereas \(l - l' - \gamma\) coupling is analyzed in the framework of anomalous magnetic moment type interaction (AMMI) model.
I. INTRODUCTION

In the Standard Model (SM) lepton flavor is conserved in neutral current processes at tree level. Many searches for lepton flavor changing neutral current (FCNC) processes have been performed within different extensions of the SM [1]. In this paper we study $e - \mu$, $e - \tau$ transitions in ep and $\mu - \tau$ transitions in $\mu p$ collisions. For numerical evaluations the center of mass energy and luminosity values [2] of future lepton-hadron colliders are given in Tables I and II. The two dynamical models we use allowing the above transitions are string inspired $E_6$ [3] and anomalous magnetic moment interactions AMMI [4]. The processes $ep \rightarrow \mu(\tau)X$ and $\mu p \rightarrow \tau X$ occur in t-channel exchange of a neutral vector boson, $Z$ in $E_6$ and $\gamma$ in AMMI.

In $E_6$, flavor violating $l - l' - Z$ vertices arise from the mixings between right handed components of the ordinary and new heavy charged leptons:

$$\Gamma^\mu = ig_Z b_{ll'Z} \gamma^\mu (1 + \gamma_5)$$

where $g_Z = g_e/\sin \theta_W \cos \theta_W$, $\theta_W$ is the weak mixing angle and $b_{ll'Z}$ denotes some combination of the leptonic mixing angles.

In the second model the interaction vertices $l - l' - \gamma$ are:

$$\Gamma^\mu = i\kappa_{ll'\gamma} \sigma_{\mu \nu} q''$$

where $q$ is the momentum transfer through the intermediate photon and $\kappa_{ll'\gamma} = a_{ll'\gamma}(\frac{g}{2m_e})$ denotes the anomalous magnetic transition moment.

II. ANALYSIS

Differential cross section for the subprocess $lq \rightarrow l'q$ in $E_6$ is obtained as:

$$\frac{d\sigma}{dt} = \frac{b_{ll'Z}^2 g_Z^4}{16\pi \hat{s}^2 [\hat{t} - (M_Z^2)^2 + M_Z^2 \Gamma_Z^2]} [(a_q + v_q)^2 \hat{t}^2 + (a_q + v_q)^2 (2\hat{s} - m_{\nu}) \hat{t} + 2\hat{s}(a_q^2 + v_q^2)(\hat{s} - m_{\nu}^2)]$$

where $\hat{s} = xS$ is the center of mass energy of the incoming lepton and quark. Using the experimental limits for FCNC $Z$ decays; $\text{BR}(Z \rightarrow e\mu) < 1.7 \times 10^{-6}$, $\text{BR}(Z \rightarrow e\tau) < 9.8 \times 10^{-6}$ and $\text{BR}(Z \rightarrow \mu\tau) < 1.2 \times 10^{-5}$ [5] we obtain the upper bound values of $b_{ll'Z}$.
The total cross section is obtained by folding $\hat{\sigma}$ over the parton distribution functions inside the proton \cite{6} as follow:

\[
\sigma = \int_{x_{\text{min}}}^{1} dx \int_{t_{-}}^{t_{+}} \frac{d\hat{\sigma}}{dt} f_q(x) dt
\]

(4)

where $x_{\text{min}} = \frac{m_e^2}{s}$ and $t_{+} = 0, t_{-} = -(s - m_{\mu}^2)$. These phase space boundaries are obtained in the $m_e = m_q = 0$ case. The results of the integrated cross sections for various lepton-proton colliders are presented in Table I. We see that $\sigma(ep \rightarrow \mu X) \approx 6\sigma(ep \rightarrow \mu X)$.

The differential cross section in AMMI model is calculated as:

\[
\frac{d\hat{\sigma}}{dt} = \frac{\alpha e_0^2 \kappa_{l'}^2 \kappa_{l}^2}{2s^2} \left[ m_{l'}^2 - 2s + (2s m_{l'}^2 - m_{l'}^4 - 2s^2) \right] \frac{1}{t}
\]

(5)

where $\alpha$ is the fine-structure constant and $e_0$ is the quark charge in units of the electron charge $e$. In the integral (4) we take a $t_{\text{cut}} = 0.01\text{GeV}$ to avoid a divergency due to the photon propagator. Now we use the experimental upper bounds for the flavor-violating $\mu$ and $\tau$ decays; $\text{BR}(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$, $\text{BR}(\tau \rightarrow e\gamma) < 2.7 \times 10^{-6}$ and $\text{BR}(\tau \rightarrow \mu\gamma) < 1.1 \times 10^{-6}$ to put the limits on $a_{l'\gamma}$:

- $a_{\mu e\gamma} < 6.36 \times 10^{-13}$
- $a_{\tau e\gamma} < 1.24 \times 10^{-8}$
- $a_{\tau \mu\gamma} < 0.79 \times 10^{-8}$

The results for the integrated cross-sections are given in Table II.

| colliders  | $\sqrt{S}(\text{GeV})$ | $\mathcal{L}(\text{cm}^{-2}\text{s}^{-1})$ | $\sigma(ep \rightarrow \mu X)(\text{pb})$ | $\sigma(ep \rightarrow \tau X)(\text{pb})$ | $\sigma(\mu p \rightarrow \tau X)(\text{pb})$ |
|------------|------------------------|------------------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Thera 1    | 1000                   | $4 \times 10^{30}$                      | $0.96 \times 10^{-2}$          | $5.57 \times 10^{-2}$          | -                               |
| Thera 2    | 1000                   | $2.5 \times 10^{31}$                    | $0.96 \times 10^{-2}$          | $5.57 \times 10^{-2}$          | -                               |
| Thera 3    | 1600                   | $1.6 \times 10^{31}$                    | $1.12 \times 10^{-2}$          | $6.50 \times 10^{-2}$          | -                               |
| LINAC⊗LHC  | 5300                   | $10^{33}$                                | $1.36 \times 10^{-2}$          | $7.85 \times 10^{-2}$          | -                               |
| $\mu$-Tevatron | 894                   | $10^{31}$                                | -                               | -                               | $6.48 \times 10^{-2}$          |
| $\mu p$    | 3000                   | $10^{32}$                                | -                               | -                               | $9.02 \times 10^{-2}$          |
Table I: Cross section values for the FCNC processes in E₆

| colliders  | $\sqrt{S}$(GeV) | $\mathcal{L}$(cm$^{-2}$s$^{-1}$) | $\sigma$(ep→$\mu$X)(pb) | $\sigma$(ep→$\tau$X)(pb) | $\sigma$(μp→$\tau$X)(pb) |
|------------|-----------------|-------------------------------|------------------------|-------------------------|------------------------|
| Thera 1    | 1000            | $4\times10^{30}$              | $1.71\times10^{-18}$   | $6.54\times10^{-10}$   | -                      |
| Thera 2    | 1000            | $2.5\times10^{31}$            | $1.71\times10^{-18}$   | $6.54\times10^{-10}$   | -                      |
| Thera 3    | 1600            | $1.6\times10^{31}$            | $1.81\times10^{-18}$   | $6.95\times10^{-10}$   | -                      |
| LINAC⊗LHC  | 5300            | $10^{33}$                     | $2.09\times10^{-18}$   | $8.02\times10^{-10}$   | -                      |
| $\mu$-Tevatron | 894              | $10^{31}$                     | -                      | -                       | $3.00\times10^{-10}$   |
| $\mu$p     | 3000            | $10^{32}$                     | -                      | -                       | $2.65\times10^{-10}$   |

Table II: Cross section values for the LFV processes in AMMI

III. CONCLUSION

Our main results indicate that future lepton-hadron colliders are promising machines for investigation of FCNC processes predicted by E₆ model. Unfortunately this statement is not applicable for LFV processes predicted by AMMI model. According to Table I we expect $N(e \to \tau) = 785$ and $N(e \to \mu) = 136$ events per year at LINAC⊗LHC and $N(\mu \to \tau) = 90$ events per year at $\mu$p collider. In the case of no observations of these events, our results show that about 2 order of higher accuracy comparing to the current limits will be achieved.

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