Lepton Flavor Violation Searches

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Abstract: Experimental limits obtained at lower luminosities are extrapolated to estimate the range of parameter space available with a total luminosity of one inverse femtobarn. An additional order-of-magnitude beyond present coupling limits will be available to HERA experiments with this total exposure. For the case of electron to tau transitions, this will represent a substantial extension of explored parameter space and the most sensitive search for most of the mechanisms discussed.

1 Introduction

All known lepton interactions are consistent with the hypothesis of individual lepton number conservation. Indeed, this observation introduces into the standard model (SM) three globally conserved quantum numbers (L_e, L_μ, and L_τ) for (e^-, ν_e), (μ^-, ν_μ), and (τ^-, ν_τ), respectively. Discovery of lepton flavor violation (LFV) *in any form* will signal new physics. In many SM extensions, lepton flavor violating processes are thought to occur, but their rates must be suppressed to levels consistent with experimental upper bounds.

At the electron-proton collider, observation of the process

$$e + p \to l + X \tag{1}$$

where l represents a muon (μ) or tau (τ) would provide evidence for LFV. HERA provides a very sensitive instrument to seek examples of reaction (1). With present luminosities, such searches have been performed [1, 2] with little background. Even at very high luminosities, the spectacular signature of an isolated high transverse momentum muon or tau is expected to be nearly background free.

Though there are many limits [3] on flavor-violation from low energy experiments, the most sensitive of these relate to $e \leftrightarrow \mu$ transitions. In addition, the sensitivities apply only to specific generations, typically first and/or second, of quarks involved in the transition. However at HERA, $e \leftrightarrow \mu$ and $e \leftrightarrow \tau$ transitions can be sought for a wide range of quark flavors.

We described in this introductory section the motivations and capabilities for LFV searches at HERA. Specific mechanisms involving leptoquarks are discussed in section 2 to illustrate the sensitivity of HERA and other LFV search experiments. The search technique and existing results are outlined in section 3. From these low luminosity results, we extrapolate to the high luminosity sensitivities given in section 4. This report concludes with the future prospects of LFV searches.

2 Mechanisms

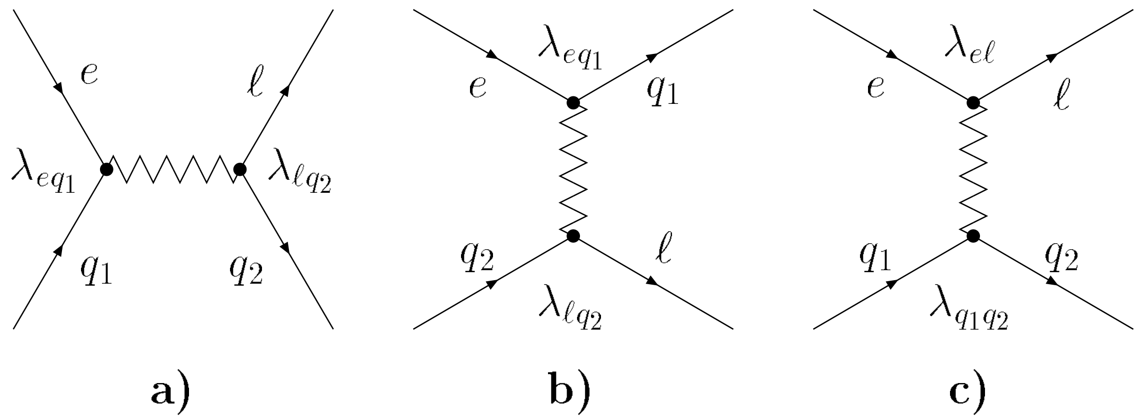

Figure 1: The (a) $s-$, (b) $u-$, and (c) $t-$channel Feynman diagrams for LFV. For the $s-$channel and $u-$channel diagrams, we denote the couplings as $\lambda_{\ell q}$, where the indices refer to the lepton and quark flavors.

Extensions of the SM typically introduce new particles and associated new couplings. The masses of new particles are assumed heavy enough and the couplings small enough so as not to effect well measured SM parameters, and not to significantly contribute through direct or virtual effects to unobserved SM forbidden processes, like $\mu \to e\gamma$ or the process (1).

For illustration, three specific mechanisms for lepton-flavor violation at HERA are shown in Figure 1. In the first two cases, leptoquarks (LQ), hypothesized bosons which provide direct connections between quark and lepton families, are responsible for the transition. The rate for the process in (1a) depends on the couplings from the initial state, λ_{eq_1}, and to the final state, λ_{lq_2}, and to the leptoquark mass, M_{LQ}. We use leptoquark mechanisms here to illustrate and compare the sensitivity to LFV from HERA with that of other experiments. It should be noted that two SUSY mechanisms producing LFV, involving non-conservation of R-parity, are equivalent to two specific leptoquark types [4].

The effective chiral LQ interaction Lagrangian with $SU(3) \otimes SU(2) \otimes U(1)$ symmetry [5] permits fourteen different types of leptoquarks with differing spin, weak isospin, and chirality. Given that reaction (1) could have either a μ or τ in the final state, that there are fourteen different leptoquark couplings, and that there are nine different combinations of quarks possible in the initial and final states, there are 252 different possible ways in which flavor-violation could be manifest in reaction (1) from leptoquark mechanisms alone.

3 Technique

In this report, we recall the sensitivity to LFV provided at HERA by ZEUS [2] with center of mass energy $\sqrt{s} = 300\ GeV$ using integrated luminosities of $0.84\ pb^{-1}$ with e^-p and $2.94\ pb^{-1}$ with e^+p, and indicate how this might be expected to improve for a scenario in which there exists 500 pb^{-1} for both e^-p and e^+p. For illustration, we indicate how the 95% confidence limits would improve for the situation in which no LFV were found.

The search in reference [2] involved specific cuts to identify isolated final state muons or taus (in all decay modes) with large transverse momenta. The search specifically required large missing transverse momentum *as observed in the calorimeter* to be greater than 12 GeV. No candidates survived all the selections, so that limits were obtained on the couplings and leptoquark masses.

The cross section for low LQ mass, $\sqrt{s} \gg M_{LQ}$ depends on the product $\lambda_{eq_1}\sqrt{B_{lq_2}}$ and on M_{LQ}. Here B_{lq_2} is the branching fraction into the observed final state. For high LQ mass, $\sqrt{s} \ll M_{LQ}$, the cross section depends on the single factor

$$\Psi = \left[\frac{\lambda_{eq_1}\lambda_{lq_2}}{{M_{LQ}}^2}\right] \tag{2}$$

As illustration of the low mass sensitivity, figure 2 shows the coupling limits versus leptoquark mass obtained to date for a few representative cases. Already with 3.8 pb^{-1} luminosity, HERA has probed leptoquark coupling strengths as small as $10^{-3}\alpha_{em}$, where α_{em} is the fine-structure constant. The HERA limits at low mass are better in all cases shown in figure 2 for any leptons involved with third generation quarks and for any quarks involved in $e \to \tau$ transitions. As we show below, all such limits will extend down by about an order-of-magnitude with the full 1 fb^{-1} luminosity.

4 High Luminosity

The high LQ mass limits for the parameter Ψ (with $M_{LQ} = 100\,GeV$) are given in tables 2-5. Here tables 2 and 3 apply for $e \leftrightarrow \mu$ transitions with LQ fermion numbers two and zero, respectively. Tables 4 and 5 apply for $e \leftrightarrow \tau$ transitions. The asterisk indicates cases in which the top quark must be involved. The four elements listed in each table entry are defined in table 1.

Process which defined previous best limit
Previous best limit for Ψ
Best limit from ZEUS with 3.8 pb^{-1}
Best limit expected with 1 fb^{-1}

Table 1: Items listed in each box of the subsequent tables.

The best limit to be expected in the 1 fb^{-1} case is obtained using the calculated efficiencies and backgrounds after optimizing the cut on missing transverse momentum. This was obtained after recognizing that the largest backgrounds are expected from processes involving $\gamma + \gamma \to \mu + \mu$ and $\gamma + \gamma \to \tau + \tau$. Monte Carlo calculations indicate that these backgrounds will remain small if the cut on missing transverse momentum is raised, for high luminosity, from 12 GeV to 25 GeV. The background cross section with this cut is estimated to be approximately 18 fb.

Though additional selections might lower this cross-section, we have not attempted to optimize to this level of detail.

In tables 2-5, we indicate by bold-face those cases in which the existing HERA limit (third entry) supersedes the previous best limit. We also indicate by bold face those cases in which the expected high luminosity limit will supersede the previous best limit.

Note that, for the $e \leftrightarrow \mu$ cases in tables 2-3, there are ten cases in which the present ZEUS limits supersede previous best limits, though in most cases these are only marginally better. (In three cases, the new limit is significantly better.) In all cases, we expect the integrated luminosity of 1 fb^{-1} to explore approximately an order of magnitude further of coupling parameter space.

For the $e \leftrightarrow \tau$ cases in tables 4-5, by contrast, there are twenty-three instances in which HERA is already exploring new parameter space. With a luminosity of 1 fb^{-1}, HERA should have become the principal instrument in such searches. Tables 4-5 indicate that over half the spaces will have been explored best at HERA. Of the remaining spaces, many involve transitions requiring participation by third generation up quarks (top), shown as asterisks.[1]

5 Conclusion

Soon after the discovery of the muon more than a half century ago, searches for lepton flavor violation began with the expected $\mu \to e\gamma$ decay mode. In addition to this classic process, other LFV reactions have been extensively sought. In the meantime, the number of LFV possibilities has increased with the discovery of the tau lepton. New opportunities for testing lepton flavor conservation have arisen using high energy colliders, like the ones for HERA described in this report.

Many models are severely restricted by the present experimental constraints on LFV, but some ideas, like the left-right symmetric models [6], predict LFV to be close to the observable range. The next generation of high-sensitivity experiments seeking forbidden kaon decay and muon transitions should be carried out. But direct LFV searches at HERA explore transitions which may not be visible in other ways.

In summary, HERA already is an important tool in the search for lepton flavor violation. A sensitive search for muons and taus in the final state is feasible at the highest luminosities. We anticipate that the most sensitive and broadest searches for $e \leftrightarrow \tau$ will be obtained using HERA.

References

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[2] ZEUS Collaboration: M. Derrick *et al*, DESY **96-161** (1996), Submitted to Z. Phys.

[1] Low energy experiments have little sensitivity here. Measurements of top decays at the Tevatron may be the instrument of choice. HERA has some sensitivity since the center of mass energy is above top threshold. For example, at $M_{LQ} = 200\ GeV$, a HERA sensitivity involving up quark to top quark transitions with Ψ as small as 0.8 might be visible.

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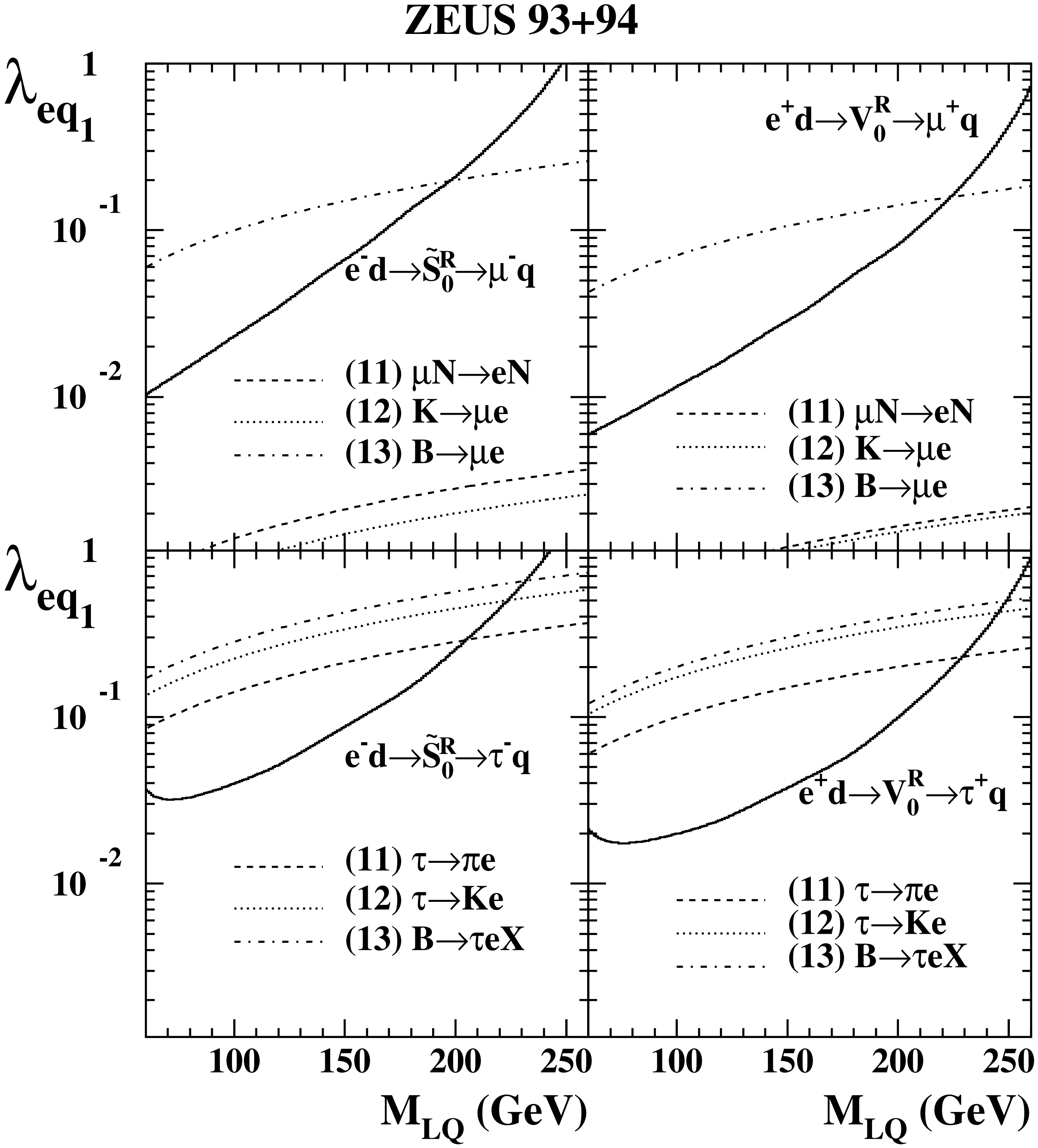

Figure 2: The 95% CL upper limits on λ_{eq_1} *vs.* leptoquark mass M_{LQ}, for selected LQ species which decay to ℓq, where $\ell = \mu$ (above) or τ (below), assuming $B_{\ell q_2} = 0.5$. The solid curves are ZEUS results [2], the various broken curves show existing limits [3]. Paired numbers in parentheses indicate the generations of the quarks which couple to e and ℓ respectively.

$e \to \mu$				$F = 2$			
$(q_1 q_2)$	S_0^L $e^- u$ $\nu\ d$	S_0^R $e^- u$	$\tilde{S}_0^R$ $e^- d$	S_1^L $e^-(u+\sqrt{2}d)$ $\nu\ (\sqrt{2}u+d)$	$V_{1/2}^L$ $e^- d$ $\nu\ d$	$V_{1/2}^R$ $e^-(u+d)$	$\tilde{V}_{1/2}^L$ $e^- u$ $\nu\ u$
(11)	$\mu N \to eN$ 2×10^{-6} 0.09 0.009	$\mu N \to eN$ 2×10^{-6} 0.09 0.009	$\mu N \to eN$ 2×10^{-6} 0.12 0.012	$\mu N \to eN$ 5×10^{-7} 0.05 0.005	$\mu N \to eN$ 7×10^{-7} 0.05 0.006	$\mu N \to eN$ 4×10^{-7} 0.03 0.004	$\mu N \to eN$ 7×10^{-7} 0.04 0.005
(12)	$K \to \pi\bar{\nu}\nu$ 2×10^{-5} 0.12 0.010	$D \to \mu\bar{e}$ 0.14 **0.12** **0.010**	$K \to \mu\bar{e}$ 10^{-6} 0.14 0.013	$K \to \mu\bar{e}$ 6×10^{-7} 0.06 0.005	$K \to \mu\bar{e}$ 6×10^{-7} 0.09 0.009	$K \to \mu\bar{e}$ 6×10^{-7} 0.06 0.006	$D \to \mu\bar{e}$ 0.07 0.08 **0.008**
(13)	V_{ub} 0.004 0.101	*	$B \to \mu\bar{e}$ 0.01 0.15 0.013	V_{ub} 0.004 0.07 0.007	$B \to \mu\bar{e}$ 0.005 0.10 0.010	$B \to \mu\bar{e}$ 0.005 0.10 0.010	*
(21)	$K \to \pi\bar{\nu}\nu$ 2×10^{-5} 0.12 0.016	$D \to \mu\bar{e}$ 0.14 **0.12** **0.016**	$K \to \mu\bar{e}$ 10^{-6} 0.14 0.018	$K \to \mu\bar{e}$ 6×10^{-7} 0.06 0.008	$K \to \mu\bar{e}$ 6×10^{-7} 0.05 0.007	$K \to \mu\bar{e}$ 6×10^{-7} 0.03 0.004	$D \to \mu\bar{e}$ 0.07 **0.04** **0.005**
(22)	$\mu \to e\gamma$ 2×10^{-4} 0.24 0.029	$\mu \to e\gamma$ 2×10^{-4} 0.24 0.029	$\mu \to e\gamma$ 8×10^{-5} 0.20 0.024	$\mu \to e\gamma$ 4×10^{-5} 0.09 0.011	$\mu \to e\gamma$ 0.15 **0.10** **0.012**	$\mu \to e\gamma$ 6×10^{-3} 0.08 0.009	$\mu \to e\gamma$ 6×10^{-3} 0.13 0.015
(23)	$B \to \ell\nu X$ 0.04	*	$B \to \bar{\mu}eK$ 6×10^{-3} 0.21 0.026	$B \to \bar{\mu}eK$ 3×10^{-3} 0.11 0.013	$B \to \bar{\mu}eK$ 3×10^{-3} 0.13 0.016	$B \to \bar{\mu}eK$ 3×10^{-3} 0.13 0.016	*
(31)	V_{ub} 0.004	*	$B \to \mu\bar{e}$ 0.01 0.16 0.020	V_{ub} 0.004 0.08 0.010	$B \to \mu\bar{e}$ 0.005 0.05 0.007	$B \to \mu\bar{e}$ 0.005 0.05 0.007	*
(32)	$B \to \ell\nu X$ 0.04	*	$B \to \bar{\mu}eK$ 6×10^{-3} 0.26 0.031	$B \to \bar{\mu}eK$ 3×10^{-3} 0.13 0.016	$B \to \bar{\mu}eK$ 3×10^{-3} 0.11 0.013	$B \to \bar{\mu}eK$ 3×10^{-3} 0.11 0.013	*
(33)		*	$\mu \to e\gamma$ 8×10^{-5} 0.29 0.036	$\mu \to e\gamma$ 4×10^{-5} 0.14 0.018	$\mu \to e\gamma$ 0.01 0.15 0.018	$\mu \to e\gamma$ 0.01 0.15 0.018	*

Table 2: Limits on flavor violation for the lepton transitions and leptoquark fermion number indicated in the first row of the table. The entries in each box are described in table 1.

$e \to \mu$ $F=0$							
$(q_1 q_2)$	$S^L_{1/2}$ $e^- \bar{u}$ $\nu\ \bar{u}$	$S^R_{1/2}$ $e^-(\bar{u}+\bar{d})$	$\tilde{S}^L_{1/2}$ $e^- \bar{d}$ $\nu\ \bar{d}$	V^L_0 $e^- \bar{d}$ $\nu\ \bar{u}$	V^R_0 $e^- \bar{d}$	$\tilde{V}^R_0$ $e^- \bar{u}$	V^L_1 $e^-(\sqrt{2}\bar{u}+\bar{d})$ $\nu\ (\bar{u}+\sqrt{2}\bar{d})$
(11)	$\mu N \to eN$ 2×10^{-6} 0.07 0.009	$\mu N \to eN$ 7×10^{-7} 0.06 0.007	$\mu N \to eN$ 2×10^{-6} 0.10 0.012	$\mu N \to eN$ 7×10^{-7} 0.06 0.006	$\mu N \to eN$ 7×10^{-7} 0.06 0.006	$\mu N \to eN$ 7×10^{-7} 0.04 0.005	$\mu N \to eN$ 3×10^{-7} 0.02 0.002
(12)	$D \to \mu\bar{e}$ 0.14 **0.08** **0.010**	$K \to \mu\bar{e}$ 10^{-6} 0.06 0.008	$K \to \mu\bar{e}$ 10^{-6} 0.10 0.013	$K \to \mu\bar{e}$ 6×10^{-7} 0.07 0.009	$K \to \mu\bar{e}$ 6×10^{-7} 0.07 0.009	$D \to \mu\bar{e}$ 0.07 **0.06** **0.008**	$K \to \mu\bar{e}$ 6×10^{-7} 0.03 0.004
(13)	*	$B \to \mu\bar{e}$ 0.01 0.11 0.013	$B \to \mu\bar{e}$ 0.01 0.11 0.013	V_{bu} 0.002 0.08 0.010	$B \to \mu\bar{e}$ 0.005 0.08 0.010	*	V_{bu} 0.002 0.08 0.009
(21)	$D \to \mu\bar{e}$ 0.14 0.17 **0.016**	$K \to \mu\bar{e}$ 10^{-6} 0.12 0.012	$K \to \mu\bar{e}$ 10^{-6} 0.17 0.018	$K \to \mu\bar{e}$ 6×10^{-7} 0.07 0.007	$K \to \mu\bar{e}$ 6×10^{-7} 0.07 0.007	$D \to \mu\bar{e}$ 0.07 **0.06** **0.005**	$K \to \mu\bar{e}$ 6×10^{-7} 0.03 0.002
(22)	$\mu \to e\gamma$ 5×10^{-5} 0.24 0.029	$\mu \to e\gamma$ 5×10^{-5} 0.16 0.018	**0.20** **0.024**	$\mu \to e\gamma$ 0.07 0.10 **0.012**	$\mu \to e\gamma$ 0.07 0.10 **0.012**	$\mu \to e\gamma$ 9×10^{-3} 0.13 0.015	$\mu \to e\gamma$ 5×10^{-3} 0.05 0.006
(23)	*	$B \to \bar{\mu}eK$ 6×10^{-3} 0.21 0.026	$B \to \bar{\mu}eK$ 6×10^{-3} 0.21 0.026	$B \to \bar{\mu}eK$ 3×10^{-3} 0.13 0.016	$B \to \bar{\mu}eK$ 3×10^{-3} 0.13 0.016	*	$B \to \bar{\mu}eK$ 3×10^{-3} 0.13 0.016
(31)	*	$B \to \mu\bar{e}$ 0.01 0.20 0.020	$B \to \mu\bar{e}$ 0.01 0.20 0.020	V_{bu} 0.002 0.07 0.007	$B \to \mu\bar{e}$ 0.005 0.07 0.007	*	V_{bu} 0.002 0.07 0.006
(32)	*	$B \to \bar{\mu}eK$ 6×10^{-3} 0.26 0.031	$B \to \bar{\mu}eK$ 6×10^{-3} 0.26 0.031	$B \to \bar{\mu}eK$ 3×10^{-3} 0.11 0.013	$B \to \bar{\mu}eK$ 3×10^{-3} 0.11 0.013	*	$B \to \bar{\mu}eK$ 3×10^{-3} 0.11 0.013
(33)	*	**0.29** **0.036**	**0.29** **0.036**	$\mu \to e\gamma$ 0.001 0.15 0.018	$\mu \to e\gamma$ 0.001 0.15 0.018	*	$\mu \to e\gamma$ 0.001 0.15 0.018

Table 3: Limits on flavor violation for the lepton transitions and leptoquark fermion number indicated in the first row of the table. The entries in each box are described in table 1.

$e \to \tau$				$F=2$			
$(q_1 q_2)$	S_0^L $e^- u$ $\nu\ d$	S_0^R $e^- u$	$\tilde{S}_0^R$ $e^- d$	S_1^L $e^-(u+\sqrt{2}d)$ $\nu\ (\sqrt{2}u+d)$	$V_{1/2}^L$ $e^- d$ $\nu\ d$	$V_{1/2}^R$ $e^-(u+d)$	$\tilde{V}_{1/2}^L$ $e^- u$ $\nu\ u$
(11)	G_F 0.003 0.15 0.014	$\tau \to \pi e$ 0.02 0.15 **0.014**	$\tau \to \pi e$ 0.02 0.23 0.021	G_F 0.003 0.09 0.008	$\tau \to \pi e$ 0.01 0.09 0.011	$\tau \to \pi e$ 0.005 0.05 0.006	$\tau \to \pi e$ 0.01 0.06 **0.007**
(12)	$K \to \pi\bar{\nu}\nu$ 2×10^{-5} 0.20 0.016	**0.20** **0.016**	$\tau \to Ke$ 0.05 0.27 **0.024**	$K \to \pi\bar{\nu}\nu$ 2×10^{-5} 0.11 0.010	$K \to \pi\bar{\nu}\nu$ 10^{-5} 0.19 0.017	$\tau \to Ke$ 0.03 0.13 **0.010**	**0.16** **0.013**
(13)	V_{bu} 0.004	*	$B \to \tau\bar{e}X$ 0.08 0.28 **0.025**	V_{bu} 0.004 0.14 0.012	$B \to \tau\bar{e}X$ 0.04 0.23 **0.020**	$B \to \tau\bar{e}X$ 0.04 0.23 **0.020**	*
(21)	$K \to \pi\bar{\nu}\nu$ 2×10^{-5} 0.22 0.026	**0.22** **0.026**	$\tau \to Ke$ 0.05 0.31 **0.035**	$K \to \pi\bar{\nu}\nu$ 2×10^{-5} 0.12 0.014	$K \to \pi\bar{\nu}\nu$ 10^{-5} 0.09 0.012	$\tau \to Ke$ 0.03 0.05 **0.007**	**0.06** **0.008**
(22)	$\tau \to e\gamma$ 0.5 0.60 **0.071**	$\tau \to e\gamma$ 0.5 0.60 **0.071**	$\tau \to e\gamma$ 0.3 0.48 **0.050**	$\tau \to e\gamma$ 0.1 0.22 **0.024**	**0.25** **0.025**	**0.19** **0.021**	**0.31** **0.036**
(23)	$B \to \ell\nu X$ 0.04	*	$B \to \tau\bar{e}X$ 0.08 0.50 **0.056**	$B \to \ell\nu X$ 0.04 0.25 **0.028**	$B \to \tau\bar{e}X$ 0.04 0.33 **0.037**	$B \to \tau\bar{e}X$ 0.04 0.33 **0.037**	*
(31)	$B \to \ell\nu X$ 0.04	*	$B \to \tau\bar{e}X$ 0.08 0.34 **0.040**	$B \to \ell\nu X$ 0.04 0.17 **0.020**	$B \to \tau\bar{e}X$ 0.04 0.10 **0.012**	$B \to \tau\bar{e}X$ 0.04 0.10 **0.012**	*
(32)	$B \to \ell\nu X$ 0.04	*	$B \to \tau\bar{e}X$ 0.08 0.65 **0.073**	$B \to \ell\nu X$ 0.04 0.32 **0.037**	$B \to \tau\bar{e}X$ 0.04 0.26 **0.028**	$B \to \tau\bar{e}X$ 0.04 0.26 **0.028**	*
(33)		*	$\tau \to e\gamma$ 0.3 0.72 **0.092**	$\tau \to e\gamma$ 0.1 0.36 **0.046**	**0.38** **0.046**	**0.38** **0.046**	*

Table 4: Limits on flavor violation for the lepton transitions and leptoquark fermion number indicated in the first row of the table. The entries in each box are described in table 1.

$e \to \tau$ $\quad F = 0$							
$(q_1 q_2)$	$S^L_{1/2}$ $e^- \bar{u}$ $\nu\ \bar{u}$	$S^R_{1/2}$ $e^-(\bar{u}+\bar{d})$	$\tilde{S}^L_{1/2}$ $e^- \bar{d}$ $\nu\ \bar{d}$	V^L_0 $e^- \bar{d}$ $\nu\ \bar{u}$	V^R_0 $e^- \bar{d}$	$\tilde{V}^R_0$ $e^- \bar{u}$	V^L_1 $e^-(\sqrt{2}\bar{u}+\bar{d})$ $\nu\ (\bar{u}+\sqrt{2}\bar{d})$
(11)	$\tau \to \pi e$ 0.02 0.11 **0.014**	$\tau \to \pi e$ 0.01 0.09 **0.007**	$\tau \to \pi e$ 0.02 0.18 0.021	G_F 0.002 0.11 0.011	$\tau \to \pi e$ 0.01 0.11 0.011	$\tau \to \pi e$ 0.01 0.07 **0.007**	G_F 0.002 0.04 0.003
(12)	**0.12** **0.016**	$\tau \to K e$ 0.05 0.10 **0.008**	$K \to \pi \bar{\nu} \nu$ 2×10^{-5} 0.18 0.024	$\tau \to K e$ 0.03 0.15 **0.017**	$\tau \to K e$ 0.03 0.15 **0.017**	**0.10** **0.013**	$K \to \pi \bar{\nu} \nu$ 5×10^{-6} 0.05 0.006
(13)	*	$B \to \tau \bar{e} X$ 0.08 0.18 **0.013**	$B \to \tau \bar{e} X$ 0.08 0.18 **0.025**	$B \to \ell \nu X$ 0.02 0.16 **0.020**	$B \to \tau \bar{e} X$ 0.04 0.16 **0.020**	*	$B \to \ell \nu X$ 0.02 0.16 **0.019**
(21)	**0.34** **0.026**	$\tau \to K e$ 0.05 0.26 **0.012**	$K \to \pi \bar{\nu} \nu$ 2×10^{-5} 0.39 0.035	$\tau \to K e$ 0.03 0.14 **0.012**	$\tau \to K e$ 0.03 0.14 **0.012**	**0.10** **0.008**	$K \to \pi \bar{\nu} \nu$ 5×10^{-6} 0.05 0.004
(22)	$\tau \to e \gamma$ 0.2 0.60 **0.071**	$\tau \to e \gamma$ 0.2 0.37 **0.018**	**0.48** **0.050**	**0.25** **0.025**	**0.25** **0.025**	**0.31** **0.036**	**0.13** **0.015**
(23)	*	$B \to \tau \bar{e} X$ 0.08 0.50 **0.026**	$B \to \tau \bar{e} X$ 0.08 0.50 **0.026**	$B \to \ell \nu X$ 0.02 0.33 0.056	$B \to \tau \bar{e} X$ 0.04 0.33 **0.037**	*	$B \to \ell \nu X$ 0.02 0.33 0.037
(31)	*	$B \to \tau \bar{e} X$ 0.08 0.47 **0.020**	$B \to \tau \bar{e} X$ 0.08 0.47 **0.040**	V_{bu} 0.002 0.15 0.012	$B \to \tau \bar{e} X$ 0.04 0.15 **0.012**	*	V_{bu} 0.002 0.15 0.011
(32)	*	$B \to \tau \bar{e} X$ 0.08 0.65 **0.031**	$B \to \tau \bar{e} X$ 0.08 0.65 **0.073**	$B \to \ell \nu X$ 0.02 0.26 0.028	$B \to \tau \bar{e} X$ 0.04 0.26 **0.028**	*	$B \to \ell \nu X$ 0.02 0.26 0.028
(33)	*	**0.72** **0.036**	**0.72** **0.092**	$\tau \to e \gamma$ 3.4 **0.38** **0.046**	$\tau \to e \gamma$ 3.4 **0.38** **0.046**	*	**0.38** **0.046**

Table 5: Limits on flavor violation for the lepton transitions and leptoquark fermion number indicated in the first row of the table. The entries in each box are described in table 1.