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LIMITS ON A LEPTON NUMBER VIOLATING PROCESS FROM e^+e^- COLLISIONS*

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ABSTRACT

If a new hypothetical particle induces a lepton number violating process, it could also affect the reactions $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ through the t-channel exchange of the particle. A fit of the cross sections and forward-backward asymmetries measured by experiments at PEP and PETRA yields the 90% confidence level limits on the coupling of the particle: $G_{e\mu} < 0.119 G_F$ and $G_{e\tau} < 0.085 G_F$, where G_F is the Fermi coupling constant. These limits exclude certain regions of couplings allowed by other lepton number violating searches.

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The search for a lepton number violating process has long been a tradition of particle physics. In recent years the immense interest in models that go beyond the standard model, such as compositeness, technicolor, lepto-quarks, and new horizontal gauge bosons, has intensified interest in the search.[1] The lepton number violating process has been sought in purely leptonic processes such as $\mu^- \to e^-e^+e^-$, $\tau^- \to \mu^-e^+e^-$, $\mu^+e^- \to \mu^-e^+$, and in semi-leptonic processes such as $e^-N \to \mu^-N$, $K^+ \to \pi^+e^+\mu^-$, $K_L^0 \to e^+\mu^-$. If a new hypothetical particle Z' induces one of the lepton number violating processes, it could also affect the reactions $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ through the t-channel exchange of Z'. Within this context, we analyze the effect of such a Z' on the cross sections and forward-backward asymmetries of these reactions and present new limits on the coupling. In the context of compositeness, Eichten, Lane and Peskin[2] have analyzed, in Bhabha and μ-pair production, the deviation in the angular distribution of the cross section from the electroweak expectation, and obtained limits on the composite energy scale. The limits obtained in this paper can be related to the composite limits if the t-channel exchange is initiated by compositeness, because both analyses assume a four-fermion point interaction as discussed below.

The reaction $e^+e^- \to \mu^+\mu^-$ could proceed through the t-channel exchange of Z' as shown in Fig. 1c. We assume that Z' has no diagonal coupling. In order to obtain a limit on the coupling of Z', it is necessary to make an assumption on the form of interaction. To facilitate comparison with the limits from other lepton number violating processes, the interaction is assumed to be a four-fermion point interaction of the form,

$$\mathcal{L} = \frac{G}{\sqrt{2}} \bar{u}_\mu \gamma_\alpha (g'_\nu - g'_a \gamma_5) u_e \bar{v}_\mu \gamma^\alpha (g'_\nu - g'_a \gamma_5) v_e \quad ,$$

where G is the interaction coupling strength, g'_ν and g'_a are the vector and axial-vector coupling constants, with $g'_\nu = g'_a = 1$ for a V–A interaction. The unpolarized differential cross section for the process, including the γ and Z^0 annihilation diagrams of Fig. 1, is given by,

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} \Big\{ (1+\cos^2\theta) \Big[1 + 2g_\nu^2\, Re\,\chi_1 + (g_\nu^2 + g_a^2)^2 \,|\chi_1|^2$$

$$+ \frac{1}{2}\,(g_\nu'^2 + g_a'^2)\chi_2 + \frac{1}{8}\left((g_\nu'^2 + g_a'^2)^2 + 4g_\nu'^2 g_a'^2\right)\chi_2^2$$

$$+ \frac{1}{2}\left((g_\nu^2 + g_a^2)(g_\nu'^2 + g_a'^2) + 4g_\nu g_a g_\nu' g_a'\right)\chi_2 Re\,\chi_1 \Big]$$

$$+ \cos\theta \Big[4g_a^2 Re\,\chi_1 + 8g_\nu^2 g_a^2 |\chi_1|^2$$

$$+ (g_\nu'^2 + g_a'^2)\chi_2 + \frac{1}{4}\left((g_\nu'^2 + g_a'^2)^2 + 4g_\nu'^2 g_a'^2\right)\chi_2^2$$

$$+ \left((g_\nu^2 + g_a^2)(g_\nu'^2 + g_a'^2) + 4g_\nu g_a g_\nu' g_a'\right)\chi_2 Re\,\chi_1 \Big]$$

$$+ \frac{1}{2}(g_\nu'^2 - g_a'^2)^2\,\chi_2^2 \Big\}$$

where

$$\chi_1 = \frac{\sqrt{2}G_F}{4\pi\alpha} \cdot \frac{sM_Z^2}{s - M_Z^2 + i\Gamma_Z M_Z} \quad ,$$

$$\chi_2 = -\frac{\sqrt{2}Gs}{4\pi\alpha} \quad ,$$

$\sqrt{s}$ is the center-of-mass energy, α is the fine structure constant, G_F is the Fermi coupling constant, M_Z and Γ_Z are the mass and width of the Z^0, g_ν and g_a are the vector and axial-vector couplings of the leptons to the Z^0: $g_\nu = -\frac{1}{2} + 2\sin^2\theta_W$ and $g_a = -\frac{1}{2}$.

The addition of the t-channel exchange diagram modifies both the cross section and the forward-backward asymmetry[3] of the reaction. At PEP and PETRA energies, for $G < G_F$, the effect mainly comes from the γ-Z' interference. The contributions from the direct Z' term and the Z^0-Z' interference term are small. At PEP energy ($\sqrt{s}$ = 29 GeV), with $G = G_F$, the γ-Z' interference decreases the cross section by $\sim$ 15% and produces an asymmetry of $\sim -11\%$, for a V–A interaction. These are to be compared with $\sim$ 0.1% and $\sim -6\%$ from the γ-Z^0 interference. Therefore, there is good sensitivity to the new particle even at PEP energy.

The limits on the couplings are extracted by performing a fit on the μ- and τ-pair cross sections and asymmetries measured by experiments at PEP and PETRA.[4] The fit takes into account correlations in the systematic errors within each experiment. In most cases, 100% correlation is assumed, except for a few measurements where it is possible to separate the correlated and uncorrelated systematic errors. The systematic errors in different experiments are assumed to be uncorrelated. The effect of a possible correlation is discussed later.

The measured cross sections and asymmetries have been corrected for the radiative corrections[5] to the γ and Z^0 exchanges. Due to the unknown nature of the Z', we do not correct for the radiative corrections involving the Z'. The corrections could reduce the final limits by a few percent as the radiated photon reduces the effective center-of-mass energy. The QED radiative correction reduces the sensitivity of the measured cross section to the Z' effect: the correction increases the cross section $R_{\ell\ell}$ (normalized to the lowest order QED cross section) by δ^{QED}, hence the sensitivity to Z' is reduced by $1+\delta^{QED}$. This correction factor depends on the cuts on the minimum lepton momentum and the maximum acolinearity angle between the leptons. These cuts are different for different experiments, although the correction is precisely known for a given set of cuts. Most experiments present the measured cross section as $R_{\ell\ell}$ after correcting for $1+\delta^{QED}$, but do not give the value of the correction. For a typical experiment, δ^{QED} is close to zero for $e^+e^- \to \mu^+\mu^-$ and $\sim 30\%$ for $e^+e^- \to \tau^+\tau^-$. The correction, averaged over all experiments, is expected to be less than 20 and 40% for the two reactions, respectively. These are the values used in the fit. The final results are relatively insensitive to the corrections because the asymmetry measurement has greater sensitivity than the cross section to Z'.

The fits on the measured cross sections and asymmetries give, for a V–A interaction,

$$G_{e\mu} = (+0.061 \pm 0.030)G_F$$
$$G_{e\tau} = (-0.020 \pm 0.049)G_F \qquad ,$$

with χ^2 of 39 for 56 degrees of freedom for the μ-pair and 28 for 36 degrees of freedom for the τ-pair. Within the errors, the results are consistent with no Z' and can be converted into upper limits on the couplings: $G_{e\mu} < 0.111 G_F$ and $G_{e\tau} < 0.080 G_F$, at the 90% confidence level. In the fits, the systematic errors in different experiments are assumed to be uncorrelated. In reality, there may be some correlation due to the theoretical uncertainty in the radiative corrections. The uncertainty is estimated to be $\pm 2\%$ for the cross section and $\pm 0.2\%$ for the asymmetry. Taking these uncertainties into account, the final results are

$$G_{e\mu} < 0.119 G_F$$

$$G_{e\tau} < 0.085 G_F \quad .$$

Assuming that Z' couples to μ and τ with the same strength, these two limits can be combined to give

$$G_{e\ell} < 0.089 G_F \quad .$$

There is no need to restrict Z' to be a V–A interaction. Other possibilities are V + A, and V or A. The limits for these possibilities are shown in Table I. The limit for a V + A interaction is similar to that for a V–A, however the limit for V or A is about a factor of two less stringent. In all cases, limits considerably below G_F are obtained.

A scalar exchange has also been studied. The differential cross section for this process is

$$\begin{aligned} \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} \Bigg\{ & (1+\cos^2\theta)\Big[1 + 2g_\nu^2 \, Re\,\chi_1 + (g_\nu^2 + g_a^2)^2 \, |\chi_1|^2 \\ & \qquad + \frac{1}{4}\chi_2 + \frac{1}{16}\chi_2^2 + \frac{1}{4}(g_\nu^2 - g_a^2)\chi_2 Re\,\chi_1\Big] \\ & + \cos\theta \Big[4g_a^2 Re\,\chi_1 + 8g_\nu^2 g_a^2 |\chi_1|^2 \\ & \qquad - \frac{1}{2}\chi_2 - \frac{1}{8}\chi_2^2 - \frac{1}{2}(g_\nu^2 - g_a^2)\chi_2 Re\,\chi_1\Big]\Bigg\} \quad . \end{aligned}$$

The limits obtained are considerably less stringent than that for a V–A interaction, although the sensitivity is still below G_F, as shown in Table I.

The limits obtained here for a V–A interaction could be compared with those from other lepton number violating processes. We assume that the same particle induces all the lepton number violating processes discussed below. The t-channel exchange in $e^+e^- \to \mu^+\mu^-$ is similar to that in $e^-e^- \to \mu^-\mu^-$. The limit obtained[6] is $G_{e\mu} < 610 G_F$. The e^+e^- result therefore offers an improvement of more than three orders of magnitude.

The t-channel exchange process is also similar to the muonium to antimuonium conversion,[7] $\mu^+e^- \to \mu^-e^+$. The limit obtained is $G_{e\mu} < 7.5\ G_F$.[8] The e^+e^- limit therefore represents an improvement of about two orders of magnitude.

If the Z' couples electrons to both the μ and the τ, then it permits the process $\tau^- \to e^-\mu^\pm e^\mp$. The width for the decay is

$$\Gamma(\tau^- \to e^-\mu^\pm e^\mp) \simeq G_{e\mu}\, G_{e\tau} \frac{m_\tau^5}{192\pi^3} \quad ,$$

where m_τ is the mass of the τ. The limit on the branching ratio[9] yields a limit on the product of couplings,

$$(G_{e\mu} G_{e\tau})^{1/2} < 1.4 \times 10^{-2} G_F \quad .$$

Therefore the limit on the product of couplings obtained in this paper is not as stringent. However, the individual limits on $G_{e\mu}$ and $G_{e\tau}$ exclude certain regions allowed by the decay search. Other limits on exotic τ decays, such as $\tau^- \to e^-e^+e^-$, $\tau^- \to e^-\mu^+\mu^-$, $\tau^- \to \mu^-\mu^+\mu^-$, produce similar limits on the product of couplings. Some of these limits involve diagonal couplings. Comparison with these limits will be meaningless if, for some unknown reasons, the diagonal couplings are very small or zero. In all cases, the limits[10] presented in this paper exclude some of the regions allowed by the decay search.

The limit on the exotic decay[11] $\mu^- \to e^- e^+ e^-$ provides a very stringent limit on the coupling,

$$(G_{e\mu} G_{ee})^{1/2} < 1.0 \times 10^{-6} \ G_F \quad .$$

Again, comparison with this limit will be meaningless if G_{ee} is very small or zero. In any case, the limit on $G_{e\mu}$ excludes some of the region allowed by the decay search. Similar stringent limits[12] have also been obtained in the K decays $K_L^0 \to e^+\mu^-$ and $K^+ \to \pi^+ e^+ \mu^-$. The limits involve the quark sector and, again, the limit on $G_{e\mu}$ excludes some of the regions allowed by the searches.

The sensitivity of the e^+e^- search increases as the square of the center-of-mass energy and will therefore continue to improve with new high energy colliders. The search in μ and K decays will eventually be limited by the background and beam intensity. Experiments at the TRISTAN e^+e^- collider could reach the sensitivity of the exotic τ decay, which is being limited by the event rate with no prospect for significant improvement in the near future. The sensitivity will be further increased at SLC and LEP if the colliders run at off the Z^0 resonance. In multi-TeV colliders, the sensitivity of the e^+e^- search will reach that in μ and K decays.

The particle being studied is assumed to be a gauge-boson like particle. Other possibilities are doubly charged Higgs or technicolor candidates. Limits on these possibilities depend on the models assumed and are not pursued here.

In conclusion, new limits are presented for searching for a lepton number violating process in e^+e^- interactions with large momentum transfer. These limits exclude certain regions of couplings allowed by other lepton number violating searches. Prospect for improvement in the near future is good.

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FIGURE CAPTIONS

1. The production of $\mu^+\mu^-$ through the t-channel exchange of Z' (c), in addition to the γ (a) and Z^0 (b) exchanges.

Table I. Upper limits on the coupling of the new particle, in unit of G_F, for V–A, V+A, V or A, and scalar interactions (at the 90% confidence level.)

	V – A	V + A	V or A	Scalar
$G_{e\mu}$	0.119	0.117	0.233	0.231
$G_{e\tau}$	0.085	0.083	0.168	0.601
$G_{e\ell}$	0.089	0.087	0.175	0.218

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2. E. J. Eichten, K. D. Lane, and M. E. Peskin, Phys. Rev. Lett. **50** (1983) 811.

3. The forward-backward asymmetry is defined as

$$A_{\ell\ell} = \frac{N_f - N_b}{N_f + N_b} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta}{\int_{-1}^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta} \quad ,$$

where N_f and N_b are the number of particles in the forward and backward regions.

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8. B. Ni *et al.*, Phys. Rev. Lett. **59** (1987) 2716.

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10. If Z' participates in diagonal interaction, the e^+e^- limits will be more stringent because of the addition of an s-channel exchange diagram.

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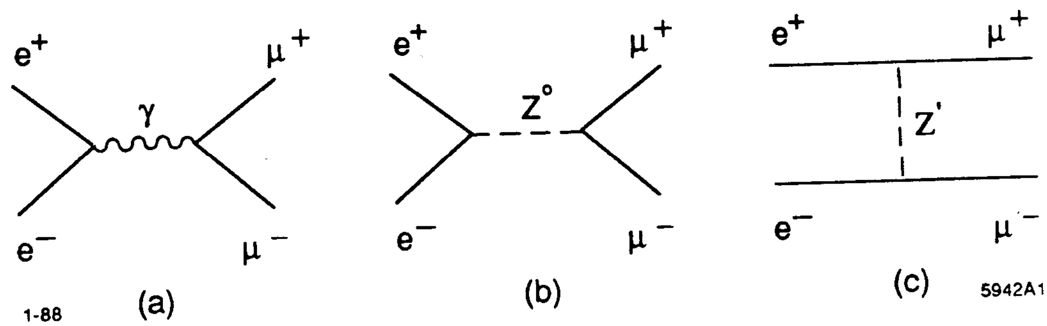

Fig. 1