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Update of the search for the neutrinoless decay $\tau \to \mu\gamma$

CLEO Collaboration

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Abstract

We present an update of the search for the lepton family number violating decay $\tau \to \mu\gamma$ using a complete CLEO II data sample of 12.6 million $\tau^+\tau^-$ pairs. No evidence of a signal has been found and the corresponding upper limit is $\mathcal{B}(\tau \to \mu\gamma) < 1.0 \times 10^{-6}$ at 90% CL, significantly smaller than previous limits. All quoted results are preliminary.

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This note summarizes results of the final search of the complete CLEO II data sample for the lepton number violating decay $\tau \to \mu\gamma$. Although there are many possible τ decay channels which do not conserve the leptonic quantum number, the decay $\tau \to \mu\gamma$ is favored by most theoretical extensions of the Standard Model [1]. The most optimistic predictions for rates of such decays are based on the supersymmetric models [2,3] and on the left-right supersymmetric models [4]. In a recent calculation [5], based on the Minimal Supersymmetric Standard Model with right-handed neutrinos, a value of 2×10^{-6} for the branching fraction for the decay $\tau \to \mu\gamma$ has been obtained for some ranges of model parameters. In general, the expectations for all other lepton number or lepton flavor violating decays of the τ are at least an order of magnitude lower. Experimental searches for the $\tau \to \mu\gamma$ decay are limited by statistics, i.e., the number of observed τ decays. The smallest upper limit [6] of $\mathcal{B}(\tau \to \mu\gamma) < 3.0 \times 10^{-6}$ at 90% CL has been published by the CLEO Collaboration using 4.24 million $\tau^+\tau^-$ pairs.

In this analysis we use a data sample from the reaction $e^+e^- \to \tau^+\tau^-$ collected at CESR at or near the energy of the $\Upsilon(4S)$. The data correspond to a total integrated luminosity of 13.8 fb^{-1} and contain about 12.6 million $\tau^+\tau^-$ pairs. The event selection follows the procedure used in the previous search [6]. We study events with a 1-vs-1 topology, where the signal candidate τ decays into $\mu\gamma$ and the tag side includes all standard τ decays into one charged particle, any number of photons and at least one neutrino.

We select $\tau^+\tau^-$ pair events with exactly two good charged tracks, with total charge equal to zero, and with an angle between the charged tracks greater than 90°. Because radiative μ-pair production provides high background rates, we allow only one identified muon per event. In addition, each candidate event must have exactly one photon separated by more than 20° from the closest charged track in the lepton hemisphere. This photon must lie in the calorimeter barrel (i.e., $|\cos\theta_\gamma| < 0.71$, where θ_γ is an angle between the photon and beam directions), have a photon-like lateral profile and have energy deposition in the calorimeter greater than 300 MeV. This minimum energy cut is dictated by the kinematics of a 2-body τ decay. The angle between the direction of the photon and the momentum of the muon track must satisfy $0.4 < \cos\theta_{\mu\gamma} < 0.8$, where the upper limit is again dictated by kinematics, and the lower limit is obtained by optimizing the signal-to-background ratio.

The main sources of background in the selected samples are due to μ-pair production, radiative $\tau \to \mu\gamma\nu\nu$ decays, and two-photon processes. To minimize these backgrounds, we require that the cosine of the angle between the total missing momentum of the event and the momentum of the tagging particle be greater than 0.4. The missing momentum is calculated as the negative of the sum of momenta of the two charged tracks and all showers detected in the calorimeter with energies above 30 MeV. Because there must be at least one undetected neutrino on the tag side, the missing momentum in an event having $\tau \to \mu\gamma$ is expected to fall into the tagging track hemisphere, while for all radiative processes the missing momentum should be uncorrelated with the charged track on the tag side. The neutrino emission on the tag side should also result in a large total transverse momentum with respect to the beam direction. Thus, to suppress background produced by copious two-photon and radiative QED processes, we require that the total transverse momentum of the event be greater than 300 MeV/c. The selection efficiency of all the previous requirements is estimated as 16.2%.

Final signal selection criteria are based on kinematic constraints since a neutrinoless τ

decay should have a total energy and an effective mass of the $\mu\gamma$ consistent with the beam energy and τ mass, respectively. To determine these final criteria, we employ two different techniques. First, we follow the method outlined in CLEO's previous search [6] for the decay $\tau \to \mu\gamma$. Then we perform a more sensitive analysis based on an unbinned extended maximum likelihood (EML) fit to the data.

Following the method described in detail in Ref. [6], we parameterize the signal Monte Carlo mass and energy distributions separately as tailed Gaussian densities. The energy density is given by:

$$f(E) = \begin{cases} \left\{ l/\left[\eta(-\tilde{E} + l/\eta - \eta)\right]\right\}^{l} \exp(-\eta^2/2) \ ; \ \tilde{E} < -\eta \ ; \\ \exp(-\tilde{E}^2/2) \ ; \ \tilde{E} > -\eta \ ; \end{cases} \qquad \tilde{E} = \frac{E - E_{beam}}{\sigma_E} \ , \tag{1}$$

where σ_E, η, and l are the fit parameters. A similar formula for the mass density is obtained by substituting the symbol "m" instead of "E" and "m_τ" instead of "E_{beam}" in the equation above. The signal region is then defined to be within ± 3 standard deviations of the fitted Gaussian component of the distribution. The τ mass, m_τ, is taken to be 1.777 GeV/c^2, and the beam energy E_{beam} varies from 5.26 to 5.29 GeV. To estimate the amount of background expected in the signal region, we extrapolate the data from the sideband. We assume that the background distributions are linear in the vicinity of m_τ and E_{beam} and define the sideband regions to be between 5 and 8 standard deviations as shown in Fig. 1. To estimate the background uncertainty associated with this technique, we vary the sideband definition. The total expected background in the signal region is estimated as 5.5 ± 0.5 events.

The upper limit on the $\tau \to \mu\gamma$ branching fraction is estimated following the Bayesian prescription [7,8]:

$$\frac{e^{-(s_0+b)} \sum_{n=0}^{n_0} \frac{(s_0+b)^n}{n!}}{e^{-b} \sum_{n=0}^{n_0} \frac{b^n}{n!}} = 0.1 \ , \tag{2}$$

where s_0 is an upper limit on the number of events in the signal region at 90% CL, b is the expected background rate, and n_0 is the number of observed events. The upper limit on the branching fraction is then:

$$\mathcal{B}(\tau \to \mu\gamma) < \frac{s_0}{2\epsilon N_{\tau\tau}} \text{ at 90\% CL} \ , \tag{3}$$

where ϵ is the event selection efficiency and $N_{\tau\tau}$ is the total number of τ-pairs produced. Applying this technique, we obtain an upper limit on the branching fraction $\mathcal{B}(\tau \to \mu\gamma)$ of 1.8×10^{-6} at 90% CL.

The systematic uncertainty in detector sensitivity $2\epsilon N_{\tau\tau}$ is conservatively estimated as 10%. This uncertainty is obtained by adding in quadrature uncertainties in track reconstruction efficiency (3%), photon reconstruction efficiency (5%), cut selection (5%), luminosity (1.4%), lepton identification (4%), Monte Carlo statistics (1.5%) and trigger efficiency (5%). The upper limit for the branching fraction is also affected by the uncertainty in background estimate: $\sigma_B = 0.5$. To incorporate systematic uncertainty into the upper limit, we assume

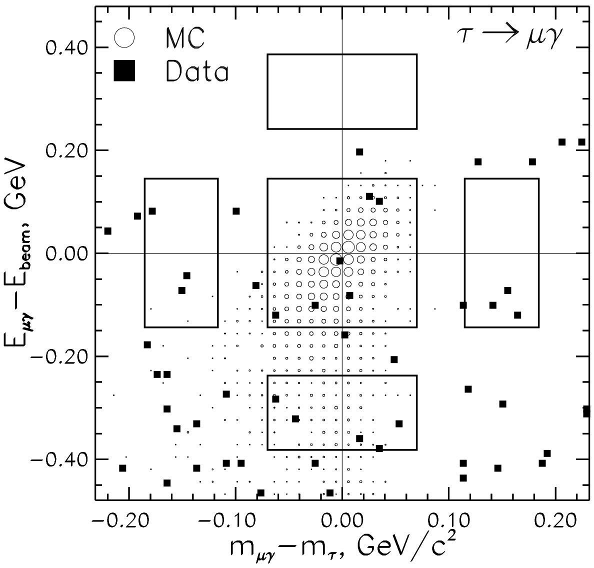

FIG. 1. $(E_{\mu\gamma} - E_{beam})$ vs $(m_{\mu\gamma} - m_\tau)$ distribution. Solid squares represent the data, open circles represent the signal Monte Carlo distribution.

that the errors related to $2\epsilon N_{\tau\tau}$ and to the background estimate have Gaussian distributions and apply a technique described in Refs. [6,9]. This technique reweights the probability (2) by a Gaussian probability density of the detector sensitivity $2\epsilon N_{\tau\tau}$ and a Gaussian probability density of the number of background events b. The incorporation of these systematic uncertainties increases the upper limit by 1.9% of itself.

A more sensitive upper limit is obtained by performing an unbinned EML fit which takes into account the details of the distributions and correlations between the mass and energy of signal event candidates. The likelihood function is defined as:

$$\mathcal{L}(s,b) = \frac{e^{-(s+b)}}{N!} \prod_{i=1}^{N} (sS_i + bB_i) \ , \qquad (4)$$

where N is the number of events in the signal region and its vicinity, s and b are the numbers of signal and background events, respectively, and S_i and B_i are the signal and background densities, respectively. The signal distribution is described by a two-dimensional Gaussian and a non-Gaussian tail in energy produced by initial and final state radiation. This tail covers the region below the beam energy and is modeled by a gamma-function.

$$S_i(m,E) = \frac{A_G}{2\pi\sigma_m\sigma_E\sqrt{1-\rho^2}} \times$$
$$\times \exp\left\{-\frac{1}{2(1-\rho^2)}\left[\left(\frac{m-m_\tau}{\sigma_m}\right)^2 - 2\rho\left(\frac{m-m_\tau}{\sigma_m}\right)\left(\frac{E-E_{beam}}{\sigma_E}\right) + \left(\frac{E-E_{beam}}{\sigma_E}\right)^2\right]\right\} +$$
$$+A_T\zeta(m,E) \; ; \tag{5}$$

$$\zeta(m,E) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma_m}\exp\left[-\frac{1}{2}\left(\frac{m-m_\tau}{\sigma_m}\right)^2\right]\frac{1}{\sigma_E\Gamma(\alpha)\beta^\alpha}\left(\frac{E_{beam}-E}{\sigma_E}\right)^{\alpha-1}\exp\left[-\frac{E_{beam}-E}{\beta\sigma_E}\right] & \text{if } E < E_{beam} \\ 0 & \text{otherwise} \end{cases}$$

where A_G and A_T are the relative contributions of the Gaussian component and the non-Gaussian tail with the sum of $A_G + A_T$ constrained to unity, σ_m and σ_E are mass and energy resolutions, respectively, ρ is the correlation coefficient, and α and β define the shape of the non-Gaussian tail $\zeta(m,E)$. To obtain the parameters of the signal density S_i, we fit the signal Monte Carlo distribution. The background is parameterized by a function linear in energy with the coefficients a_0 and a_1 obtained from a fit to the data:

$$B_i(m,E) = \frac{1}{m_2 - m_1}\frac{1}{(a_0 - a_1 E_{beam})(E_2 - E_1) + 0.5a_1(E_2^2 - E_1^2)}\left[a_0 + a_1(E - E_{beam})\right] \; , \tag{6}$$

where (m_1, m_2) and (E_1, E_2) are the limits defining the fit region. The region within 4 standard deviations near the beam energy E_{beam} is excluded from the fit to avoid bias caused by the possible presence of real signal events in this region. Uncertainties of the background shape parameters a_0 and a_1 are estimated by varying the number of bins in the fit region.

The EML fit to the data gives the number of candidates for the decay $\tau \to \mu\gamma$ as 1.8 events with an estimated statistical significance of the signal 1.0 standard deviations. The fit region, shown in Fig. 1, is defined to be within 10 standard deviations near the τ mass and beam energy. The total number of events in the fit region is 53.

To estimate the upper limit, we use a method [10] developed for unbinned EML fits. [1] For every assumed expected number of signal events s, we generate 10,000 Monte Carlo samples. For every sample, we generate numbers of signal and background events using Poisson distributions and then we generate positions of these events on the energy-vs-mass plane using the densities from Eqns. (5) and (6). For each sample we then perform an unbinned EML fit to extract the number of signal events, following the same procedure as for the data. The confidence level corresponding to this value of s is defined as a fraction of samples where the extracted number of events exceeds that observed in the data, i.e., 1.8. We repeat this procedure until we find a value of $s = s_0$ that gives a 90% CL. This value has to be divided by the selection efficiency and the number of produced τ-pairs in accordance with Eqn. (3). The obtained upper limit on the branching fraction $\mathcal{B}(\tau \to \mu\gamma)$ is 1.0×10^{-6} at 90% CL.

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[1] This method assumes a confidence interval to be from 0 to s_0 and thus gives a different upper limit than that obtained by the method of Ref. [11]. The prescription [11] has been developed for problems with integer numbers of observed signal candidate events and, in its present shape, is inapplicable to EML fits.

To incorporate systematic uncertainty into this result, we smear the background shape parameters a_0 and a_1 within the estimated uncertainties assuming Gaussian distributions and taking into account the correlation between these two parameters. We then repeat the procedure described in the previous paragraph, the only modification is that now we integrate the likelihood function over the parameter space of a_0 and a_1. Because the parameters of the signal density are known with better accuracy and because we do not observe a significant signal contribution, the result is insignificantly affected by uncertainties in the parameters of the signal density function. In addition to smearing the parameters, we integrate the quantity $1/(2\epsilon N_{\tau\tau})$ assuming a Gaussian distribution for the detector sensitivity $2\epsilon N_{\tau\tau}$ with a relative standard deviation equal to the estimated systematic uncertainty, i.e., 10%. A conservatively estimated relative effect of the systematic uncertainties on the upper limit is below 10%. Since this computation is not yet finished, we quote a result without inclusion of systematic uncertainties.

The selection efficiencies, numbers of events, and upper limits calculated for both techniques are given in Table I. This result is limited by the total integrated luminosity and represents a significant improvement over the previous analysis [6]. It also, for the first time, restricts the parameter space of some versions of the MSSM models [5].

TABLE I.
Selection efficiencies, numbers of events, and upper limits.

Method	Method of Ref. [6]	Unbinned EML fit
MC efficiency, ϵ	12.7%	15.2%
Number of signal events	$n_0 = 6$	$s = 1.8$
Expected background rate, b	5.5 ± 0.5	-
Statistical significance of the signal	-	1.0σ
Upper limit at 90% CL, s_0	5.8	3.8
Upper limit for $\mathcal{B}(\tau \to \mu\gamma)$ at 90% CL	1.8×10^{-6}	1.0×10^{-6}

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