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Search for Second-Class Currents in $\tau^- \to \omega\pi^-\nu_\tau$

The BABAR Collaboration

Abstract

We report on an analysis of τ^- decaying into $\omega\pi^-\nu_\tau$ with $\omega \to \pi^+\pi^-\pi^0$ using data containing nearly 320 million tau pairs collected with the BABAR detector at the PEP-II asymmetric energy B-Factory. We find no evidence for second-class currents and set an upper limit at 0.69% at a 90% confidence level for the ratio of second- to first-class currents.

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1 INTRODUCTION

Weak currents can be classified as either first- or second-class depending on the J^{PG} of the decay current [1], where G-parity is a combination of charge conjugation and an isospin rotation, $\hat{G} = \hat{C}e^{i\pi\hat{I}_2}$, and is a multiplicative quantum number. In the Standard Model, first-class currents (FCC), where $PG(-1)^J = +1$ ($J^{PG} = 0^{++}, 0^{--}, 1^{+-}, 1^{-+}, \ldots$), are expected to dominate decays while second-class currents (SCC), where $PG(-1)^J = -1$ ($J^{PG} = 0^{+-}, 0^{-+}, 1^{++}, 1^{--}, \ldots$), are expected to be small and to vanish in the limit of perfect isospin symmetry. An example of such a decay is $\tau^- \to \omega\pi^-\nu_\tau$[8], which is expected to proceed through FCC mediated by the ρ resonance. This decay may also potentially proceed through SCC, such as $b_1(1235)$ [2] with $\tau^- \to b_1^-\nu_\tau \to \omega\pi^-\nu_\tau$, producing final state particles with $J^{PG} = 1^{++}$ and 0^{-+}.

Since the decay $b_1^- \to \omega\pi^-$ occurs through S- and D-waves, as compared to a P-wave for FCC, different polarizations of ω spin result in different angular distributions of the final state particles. The expected distributions of $\cos\theta_{\omega\pi}$ for all possible spin-parity states of the final state particles are listed in Table 1, where $\theta_{\omega\pi}$ is the angle between the normal to the ω decay plane and the direction of the remaining π in the ω rest frame, as shown in Figure 1. The existing measurement of the angular distribution of $\tau^- \to \omega\pi^-\nu_\tau$ is consistent with having only P-wave contribution, and the present limit is 5.4% for the ratio of SCC to FCC contributions, $N^{\omega\pi}_{\text{(non-vector current)}} / N^{\omega\pi}_{\text{(vector current)}}$, at 90% confidence level [3]. This paper presents a search for SCC in $\tau^- \to \omega\pi^-\nu_\tau$ decays with $\omega \to \pi^+\pi^-\pi^0$ by studying the angular distributions of final state particles.

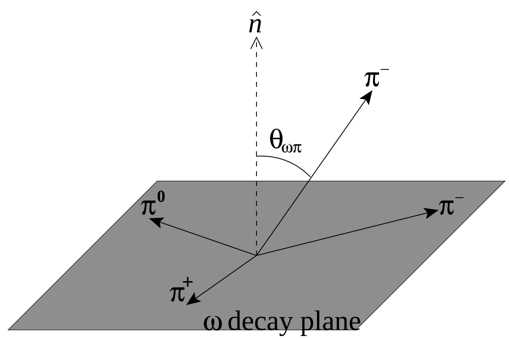


Figure 1: Illustration of the angle $\theta_{\omega\pi}$: the angle between the normal to the ω decay plane and the direction of the remaining π in the ω rest frame.

2 THE *BABAR* DETECTOR AND DATASET

This analysis is based on data recorded by the *BABAR* detector [4] at the PEP-II asymmetric-energy e^+e^- storage rings operated at the Stanford Linear Accelerator Center. The data sample consists of 347.3 fb^{-1} recorded at the center-of-mass energy of $10.58\,\text{GeV}$. With a cross section for τ pairs of $\sigma_{\tau\tau} = (0.919 \pm 0.003)$ nb [5], this data sample contains nearly 320 million pairs of tau decays.

The *BABAR* detector is described in detail in Ref. [4]. Charged-particle momenta are measured with a 5-layer double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) inside a 1.5-T superconducting solenoidal magnet. An electromagnetic calorimeter (EMC) consisting of

[8]Charge-conjugate reactions are implied throughout this paper.

Table 1: Expected angular distributions, $F_L(\cos\theta_{\omega\pi})$, for possible spin-parity states in the decay of $\tau^- \to \omega\pi^-\nu_\tau$. L is the orbital angular momentum.

J^P	L	F^{FCC}	$F_L^{SCC}(\cos\theta_{\omega\pi})$
1^-	1	$F^{FCC} \propto (1-\cos^2\theta_{\omega\pi})$	
1^+	0		$F_0^{SCC} \propto 1$
1^+	2		$F_2^{SCC} \propto (1+3\cos^2\theta_{\omega\pi})$
0^-	1		$F_1^{SCC} \propto \cos^2\theta_{\omega\pi}$

6580 CsI(Tl) crystals is used to identify electrons and photons. A ring-imaging Cherenkov detector is used to identify charged hadrons, in combination with ionization energy loss measurements (dE/dx) in the SVT and the DCH. Muons are identified by an instrumented magnetic-flux return (IFR).

Monte Carlo (MC) simulations are used to estimate the signal efficiencies and background contamination. The production of τ pairs is simulated with the `KK2f` generator [6], and the decays of the τ lepton are modeled with `Tauola` [7]. Continuum $q\overline{q}$ events are simulated using `JETSET` [8]. Final state radiative effects are simulated for all decays using `Photos` [9]. The detector response is simulated with `GEANT4` [10], and the simulated events are then reconstructed in the same manner as data.

3 ANALYSIS METHOD

Since τ pairs are produced back-to-back in the e^+e^- center-of-mass frame, each event is divided into two hemispheres according to the thrust axis [11], calculated using all reconstructed charged particle tracks. Candidate events in this analysis are required to have a "1-3 topology," where one track is in one hemisphere (tag hemisphere) and three tracks are in the other hemisphere (signal hemisphere). Events with four well-reconstructed tracks and zero net charge are selected. The polar angles, in the laboratory frame, of all four tracks and the neutrals used in π^0 reconstruction are required to be within the calorimeter acceptance range. Events are rejected if the invariant mass of pairs of oppositely charged tracks, assuming electron mass hypotheses, is less than 90 MeV/c^2, as these tracks are likely to be from photon conversions in the detector material.

The charged particle found in the tag hemisphere must be either an electron or a muon candidate. Electrons are identified using the ratio of calorimeter energy to track momentum (E/p), the shape of the shower in the calorimeter, and dE/dx. Muons are identified by hits in the IFR and small energy deposits in the calorimeter consistent with expectation for a minimum-ionizing particle. Muons with momentum less than 0.5 GeV/c cannot be identified in this manner as they do not penetrate far enough into the IFR. Charged particles found in the signal hemisphere must be identified as pion candidates using dE/dx. The π^0 candidates are reconstructed from two separate EMC clusters with energies above 100 MeV that are not not associated with charged tracks and are required to have invariant masses between 100 and 160 MeV/c^2. Events are required to have a single π^0 in the signal hemisphere. The τ candidates are reconstructed in the signal hemisphere using the three tracks and the π^0 candidate, and the invariant mass of the τ candidate, $m(2\pi^-\pi^+\pi^0)$ is required to be less than the nominal mass of the τ lepton, $m_\tau = 1.777\,\mathrm{GeV}/c^2$ [12]. After the event selection process, from the MC it is found that 14% of the events remaining are

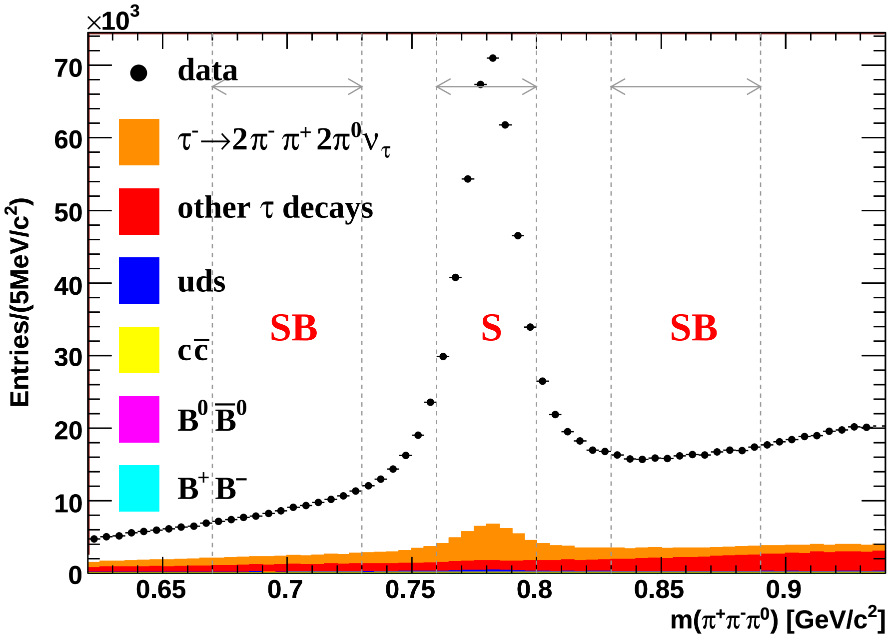


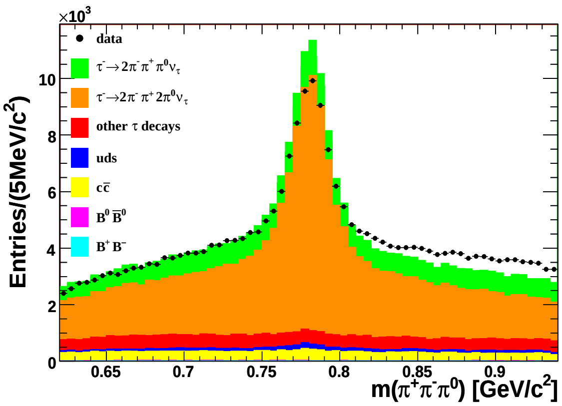
Figure 2: ω candidate mass spectra for selected events in data and expected Monte Carlo background (colored histograms). The background histograms do not include the non-resonant $\tau^- \to 2\pi^-\pi^+\pi^0\nu_\tau$ decays. The signal (S) and sideband (SB) regions are indicated in the figure.

τ-pair events that do not contain a $\tau^- \to 2\pi^-\pi^+\pi^0\nu_\tau$ decay, and 1.3% are $e^+e^- \to q\overline{q}$ events.

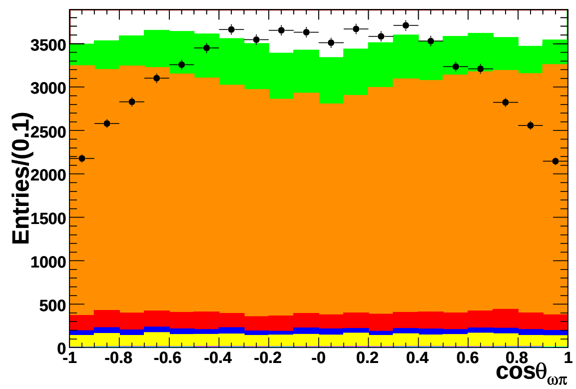
For each selected event with $m(2\pi^-\pi^+\pi^0) < m_\tau$ two ω candidates are reconstructed from $\pi^+\pi^-\pi^0$ combinations. The mass of the ω candidates, $m(\pi^+\pi^-\pi^0)$, is required to be between 670 MeV/c^2 and 890 MeV/c^2; within this range, the signal region is defined between 760 MeV/c^2 and 800 MeV/c^2 with mass regions of width 60 MeV/c^2 on each side of the peak used as sideband regions for background studies, as shown in Figure 2. For each ω candidate in the signal region, the angle $\theta_{\omega\pi}$ is calculated and is used in the SCC measurement, after background subtraction.

There are three background types to be considered in this analysis. The first type is combinatoric background, which is expected to have an angular distribution that is independent of $m(\pi^+\pi^-\pi^0)$, and is thus subtracted from the signal region using the sideband regions. The number of combinatoric events lying within the signal region is obtained by fitting the $m(\pi^+\pi^-\pi^0)$ spectrum with a smeared relativistic Breit-Wigner for the ω resonance and a polynomial for the combinatoric background. The polynomial is integrated over the signal region to find the number of continuum events in the signal region. The second type of background comes from $e^+e^- \to q\overline{q}$ events that contain $\omega \to \pi^+\pi^-\pi^0$ decays. While the event selection process significantly reduces the number of $q\overline{q}$ events, approximately 0.3% of the events in the signal region are expected to be of $q\overline{q}$ origin. This type of background is studied using events with $m(2\pi^-\pi^+\pi^0)$ well above the τ mass ($> 2.1\,\mathrm{GeV}/c^2$). In this region, where all events are considered to be of $q\overline{q}$ origin, a comparison of the numbers of events in MC and data is used to obtain a scaling factor for the $q\overline{q}$ background events.

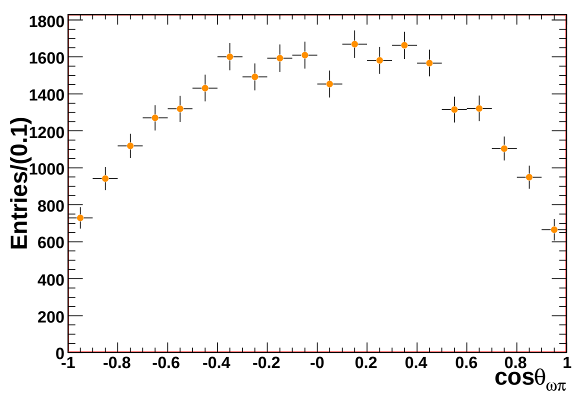
After subtracting combinatoric and $q\overline{q}$ background events, approximately 4.6% of the remaining ω candidates in the signal region are expected to be background events from non-signal τ decays. The dominant of these, comprising 99% of these background events, is $\tau^- \to \omega\pi^-\pi^0\nu_\tau$, where one π^0 has not been reconstructed. The decay $\tau^- \to \omega\pi^-\pi^0\nu_\tau$ has not been well measured and is incorrectly modeled in the MC. Both the branching fraction and decay angular distribution need to be corrected, as shown in Figures 3(a) and 3(b). To correct for the differences between data and MC, events with an additional π^0 candidate in the signal hemisphere are selected, using the same cuts discussed above. Using these events, the MC branching fraction of $\tau^- \to \omega\pi^-\pi^0\nu_\tau$ is corrected by comparing the numbers of fitted ω candidates in data and MC. The fit function used for this is a smeared relativistic Breit-Wigner with a polynomial background. The branching fraction obtained using this correction technique is found to be consistent with existing measurements [12]. To correct the angular distribution of $\tau^- \to \omega\pi^-\pi^0\nu_\tau$ in the signal region, backgrounds, consisting of combinatorics, $q\overline{q}$ events and $\tau^- \to \omega\pi^-\nu_\tau$ decays, are subtracted from the two π^0 data sample, and the remaining $\cos\theta_{\omega\pi}$ distribution, shown in Figure 3(c), is used to correct the $\tau^- \to \omega\pi^-\pi^0\nu_\tau$ distribution in the MC.



(a)



(b)



(c)

Figure 3: (a) $m(\pi^+\pi^-\pi^0)$ and (b) $\cos\theta_{\omega\pi}$ distributions when requiring an additional π^0 in the signal hemisphere, before background subtraction. These are used to correct the $\tau^- \to \omega\pi^-\pi^0\nu_\tau$ MC. (c) The $\cos\theta_{\omega\pi}$ distribution obtained from data after subtracting background.

To account for any variation in efficiency as a function of $\cos\theta_{\omega\pi}$, the generated and reconstructed MC $\cos\theta_{\omega\pi}$ distributions of $\tau^- \rightarrow \omega\pi^-\nu_\tau$ in the signal region are compared. The ratio of the two distributions, shown in Figure 4, is used as an efficiency function to correct the background subtracted data.

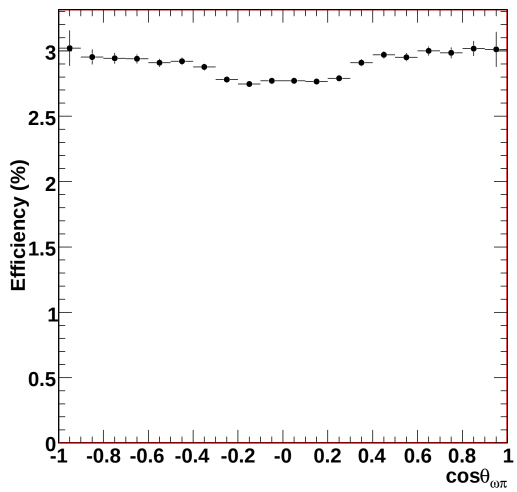


Figure 4: Efficiency as a function of $\cos\theta_{\omega\pi}$ obtained from $\tau^- \rightarrow 2\pi^-\pi^+\pi^0\nu_\tau$ MC.

4 PHYSICS RESULTS

After subtracting background events and applying efficiency corrections, a binned fit to the remaining $\cos\theta_{\omega\pi}$ distribution is carried out using

$$F(\cos\theta_{\omega\pi}) = N \times [\epsilon F_0^{SCC}(\cos\theta_{\omega\pi}) + (1-\epsilon)F^{FCC}(\cos\theta_{\omega\pi})], \quad (1)$$

where N is a normalization factor, the parameter ϵ is the fraction of $\tau^- \rightarrow \omega\pi^-\nu_\tau$ decays that proceed through SCC, and F^{FCC} and F_0^{SCC} are normalized angular functions described in Table 1. The parameter ϵ is related to $N^{\omega\pi}_{\text{(non-vector current)}} / N^{\omega\pi}_{\text{(vector current)}}$ by the equation $\varepsilon/(1-\varepsilon) = N^{\omega\pi}_{\text{(non-vector current)}} / N^{\omega\pi}_{\text{(vector current)}}$. In Eq.1, only F_0^{SCC} is used for the function describing the SCC contribution since the shape of this function gives the most conservative (largest) estimate of ϵ.

This method is tested by adding various amounts of S-wave decays to the standard MC and fitting for the levels of SCC. As the results of this test indicate, as shown in Table 2, in all cases the measured fractions of SCC, ϵ, are consistent with the fractions added to the MC. The errors listed in Table 2 are not necessarily indicative of the expected uncertainties in the data; they do not contain systematic uncertainties, and statistical correlations exist among the MC samples used in the studies.

The largest contributions to systematic uncertainties on ϵ are scaling and modeling of the MC background. The correction applied to the branching fraction of $\tau^- \rightarrow \omega\pi^-\pi^0\nu_\tau$ has an error associated with it, determined by the available statistics. The correction factor is adjusted by $\pm 1\sigma$ to obtain the uncertainty in ϵ while the errors associated with correcting the angular distribution

Table 2: Test of SCC measurements in MC with various amounts of S-wave decays added.

Fraction of $L=0$ $\tau^- \to \omega\pi^-\nu_\tau$ decays added	ϵ
none	$(0.11 \pm 0.17)\%$
1%	$(1.10 \pm 0.17)\%$
2%	$(2.09 \pm 0.17)\%$

are folded into the statistical uncertainty. In addition, there are τ decays that may be present in the final event sample but which are not simulated in the MC. The largest of these are expected to be $\tau^- \to \omega K^-\nu_\tau$, $\tau^- \to \omega\pi^-2\pi^0\nu_\tau$ and $\tau^- \to \omega 2\pi^-\pi^+\nu_\tau$ decays, which when combined can add up to 0.2% of the final event sample. Since the effect that these decays have on the angular distribution is unknown, the extreme cases are taken to obtain the uncertainty. These cases correspond to these decays having either entirely $1-\cos^2\theta_{\omega\pi}$ or entirely $\cos^2\theta_{\omega\pi}$ distributions. The scaling of $q\overline{q}$ events can also affect the measurement of ϵ, and the uncertainty is obtained by adjusting the scaling factor by $\pm 1\sigma$. These systematic uncertainties are summarized in Table 3.

Table 3: Summary of systematic uncertainties on ϵ

Source	Uncertainty (σ_ϵ)
$\mathcal{B}\,(\tau^- \to \omega\pi^-\pi^0\nu_\tau)$	± 0.0007
un-simulated τ decays	$^{+0.0000}_{-0.0055}$
$q\overline{q}$ scaling	± 0.0001
Total	$^{+0.0008}_{-0.0055}$

To estimate the sensitivity of this analysis without the effect of statistical correlations in the MC samples used, a toy MC study is conducted. In this study, angular distributions are generated for the signal and sideband regions to simulate the statistics available in the data and various MC samples used in the analysis. After subtracting background samples from the toy data, the angular distribution is corrected for efficiency and fitted using Eq.1. The statistical uncertainty on ϵ obtained from the fit is 0.0063, which combined with the systematic uncertainties leads to an estimated uncertainty of $\sigma_\epsilon =^{+0.0064}_{-0.0084}$.

With the MC studies completed, the angular distribution in the data is obtained by subtracting estimated background events as described above. The remaining distribution is corrected for efficiency and fitted using Eq. 1 as shown in Figure 5. The fit has χ^2/dof = 15.4/18, and the fitted value of ϵ in the data is $(-5.5 \pm 5.8(\text{stat})^{+0.8}_{-5.5}(\text{syst})) \times 10^{-3}$, which is consistent with no SCC contribution to $\tau^- \to \omega\pi^-\nu_\tau$ decays. For the upper limit on $N^{\omega\pi}_{(\text{non-vector current})} / N^{\omega\pi}_{(\text{vector current})}$, a Bayesian approach [13] is used as negative values of ϵ are non-physical. Using only the positive portion of the probability distribution for the value of the SCC contribution, ϵ_{true}, the distribution for ϵ_{true} is a bifurcated Gaussian with mean $\epsilon = 5.5 \times 10^{-3}$ and errors $\sigma_\epsilon =^{+0.0064}_{-0.0084}$. The limits obtained from this method are 0.69% at 90% C.L. and 0.85% at 95% C.L.

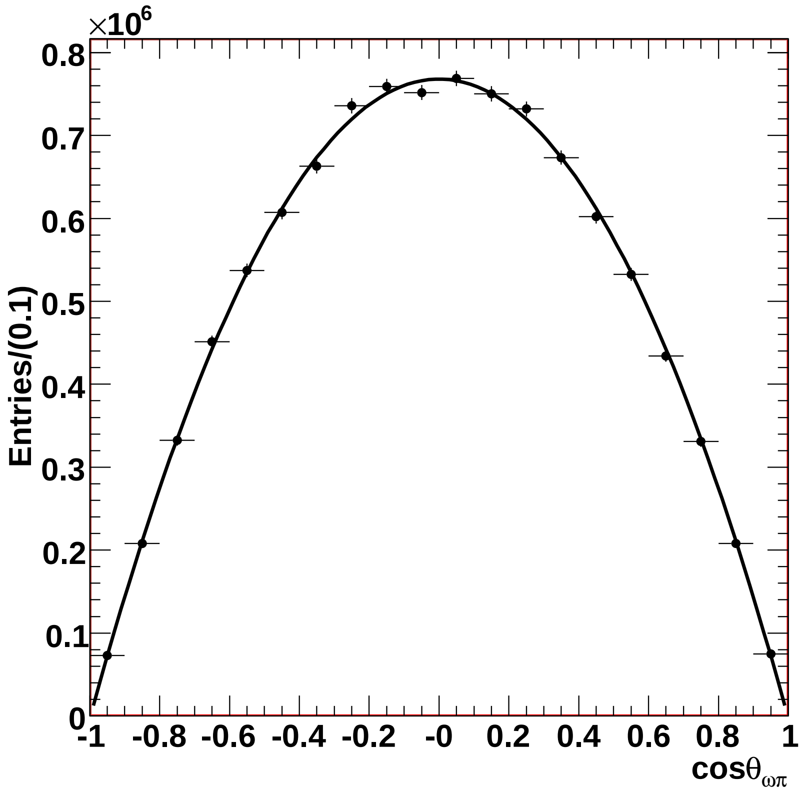


Figure 5: The fitted $\cos\theta_{\omega\pi}$ distribution for the data. The fitted curve is described in the text.

5 SUMMARY

A search for second-class currents in the decay $\tau^- \to \omega\pi^-\nu_\tau$ is conducted with the *BABAR* detector. No evidence for second-class currents is observed, and a 90% confidence level Bayesian upper limit for $N^{\omega\pi}_{\text{(non-vector current)}}$ / $N^{\omega\pi}_{\text{(vector current)}}$ is set at 0.69%. This limit is an order of magnitude lower than the limit set by the CLEO collaboration [3].

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