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Search for ϕ mesons in τ lepton decay

CLEO II Collaboration

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Abstract

We report results from a direct search for $\tau^- \to \phi X^- \nu_\tau$ ($X^- = \pi^-$or K^-) using 3.1 fb^{-1} of data taken with the CLEO II detector. We find model-dependent upper limits on the branching fractions in the range: $\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau) < 1.2-1.9\times10^{-4}$ @ 90% C.L., and $\mathcal{B}(\tau^- \to \phi K^-\nu_\tau) < 5.4-6.7\times10^{-5}$ @ 90% C.L.

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I. INTRODUCTION

A measurement of the decay $\tau^- \rightarrow \phi\pi^-\nu_\tau$ [1] is of interest as it may provide important clues to the workings of QCD at the 1 GeV/c^2 mass scale. This decay mode may serve [2] as a valuable source of information on a possible four-quark state ($C(1480)$) with mass of 1480 MeV/c^2 and $J^{PC} = 1^{--}$ [3,4] which decays into $\phi\pi$. In Ref. [5] estimates of the branching fraction of $\tau^- \rightarrow \phi\pi^-\nu_\tau$ are presented building on the work of Ref. [6] where a non-exotic explanation (the $C(1480)$ is really the $\rho(1450)$) of the state at 1480 MeV/c^2 is proposed. The authors of Ref. [5] find that the non-exotic model yields a "most optimistic" branching fraction of $\mathcal{B}(\tau^- \rightarrow \phi\pi^-\nu_\tau) = 0.02\%$. However, the branching fraction will be much smaller if the resonance is an exotic state. It is possible to estimate the branching ratio for this process, independent of the resonance assignment using the conserved vector current hypothesis (CVC) and data from e^+e^- annihilations. The upper limits on the reaction $e^+e^- \rightarrow \phi\pi^0$ from Ref. [7–9] predict an upper limit of 0.06% [10] for $\tau^- \rightarrow \phi\pi^-\nu_\tau$.

The first search for $\tau^- \rightarrow \phi\pi^-\nu_\tau$ was carried out by the CLEO experiment where a preliminary 90% confidence level upper limit of $\mathcal{B}(\tau^- \rightarrow \phi\pi^-\nu_\tau) < 2.6 \times 10^{-4}$ was reported [11]. Recently the ARGUS collaboration obtained $\mathcal{B}(\tau^- \rightarrow \phi\pi^-\nu_\tau) < 3.5 \times 10^{-4}$ [12], consistent with the CLEO result. In this work we update the CLEO result and consider several models of $\tau^- \rightarrow \phi\pi^-\nu_\tau$ and obtain upper limits for each model. In addition, we search for the decay $\tau^- \rightarrow \phi K^-\nu_\tau$ using a similar technique and present the first upper limits on the branching fraction for this decay mode.

II. ANALYSIS

This analysis uses 3.1 fb^{-1} of data taken with the CLEO II detector at the Cornell Electron Storage Ring (CESR). The CLEO II detector is described in detail in Reference [13]. The data sample used in this analysis corresponds to $\approx 2.8 \times 10^6$ produced τ pairs.

For this analysis we select τ pair events where one τ decays into a single charged track and the other τ decays into three charged tracks (1 vs 3 topology). We search these events for $\phi \rightarrow K^+K^-$ by forming the invariant mass of oppositely charged tracks, assuming the kaon mass for each track. For the reconstruction of the ϕ meson we make tight cuts on the kinematic variables involved in the production and decay of the ϕ.

To select a τ pair sample, all events are required to have 4 charged tracks with zero net charge, total missing mass squared [14] greater than zero, and the 1 vs 3 topology. To remove radiative QED background (mostly Bhabhas), events having one or more electrons on the 3-prong side are rejected. In addition, we reject events where the invariant mass of an oppositely charged pair of particles, assumed to be electron and positron, satisfies $m_{e^+e^-} \leq$ 50 MeV/c^2.

In order to distinguish τ-pair events from hadronic background ($e^+e^- \rightarrow \bar{q}q$) we use a standard statistical method, the multivariate linear discriminant technique [15,16]. For this analysis, six kinematical variables are combined in a linear fashion to form the discriminant $\Delta_{\tau\tau,hadron}$. The variables used are: the transverse momentum of the event, the missing mass in the event, the invariant mass on the 1-prong side, the invariant mass on the 3-prong side, the energy on the 1-prong side, and the energy on the 3-prong side. In Fig. 1 a), we show the distribution of $\Delta_{\tau\tau,hadron}$ for Monte Carlo τ-pairs and hadronic continuum events. For this analysis we require $\Delta_{\tau\tau,hadron} \leq -7$. This keeps 80% of the 1 vs 3 τ's and rejects 96% of hadronic continuum events. From Monte Carlo studies, the overall efficiency of the 1 vs 3 τ event selection criteria is 29% after imposing all of the above requirements. The background in the τ sample from hadronic continuum events, $\mathrm{B\bar{B}}$ events, radiative Bhabha events, μ pair events, and two photon events, is estimated, at this point in the analysis, to be less than 3%.

There is considerable uncertainty as to the mechanism responsible for the decay $\tau^- \to \phi\pi^-\nu_\tau$. In this analysis we consider Monte Carlo models of this decay both with and without intermediate states. For the model without any intermediate states, we generate Monte Carlo τ pair events in which one τ decays into $\phi\pi\nu_\tau$ according to the $V-A$ structure of weak decays and three body phase space while the other τ has one charged particle in the final state. For the model with an intermediate resonant state, we generate samples of τ pair events, in which one τ decays into ν_τ and a resonance state which decays into $\phi\pi$, while the other τ decays into one charged particle. Because we have little information on the resonance state, we select three invariant masses for the resonance: 1350, 1450, and 1650 MeV/c^2, with widths of 100, 130, 100 MeV/c^2, respectively [17]. In all Monte Carlo simulations, the ϕ always decays into K^+K^-. For the decay $\tau^- \to \phi K^-\nu_\tau$ we consider two models, phase space and a resonance at 1650 MeV/c^2, since the resonances at 1350 and 1450 MeV/c^2 would be highly suppressed by kinematics.

The search for ϕ mesons in the 3-prong decay of the τ does not use particle identification, only kinematics. To select well measured events, the tracks on the 3-prong side are required to be in the calorimeter barrel region, $|\cos\theta| < 0.707$, where θ is the angle with respect to the beam direction. In order to take advantage of the kinematics of the decay $\tau \to \phi\pi\nu$, with $\phi \to \mathrm{K^+K^-}$, the following conditions are imposed on the 3-prong side of each candidate event for all the decay models considered: i) The momentum of each kaon candidate track must satisfy $0.9 \leq |\bar{\mathbf{p}}_K| \leq 2.4$ GeV/c. ii) The angle between the two kaon candidates in the lab frame must be $\leq$0.2 radians. In addition, there must be no more than one unmatched photon candidate with energy $\geq$ 100 MeV.

After selecting the 1 vs 3 τ sample by imposing the above cuts, we find from Monte Carlo studies that most of the events in the data sample are from generic τ decays. In order to reduce the background level from these generic τ events, we again use the multivariate linear discriminant technique. This time five variables are used to define the discriminant $\Delta_{\phi\pi\nu,\tau\tau}$: the transverse momentum and missing mass of event, the invariant mass and energy of 3 charged tracks assumed to be pions, and the invariant mass of 3 charged tracks assumed to be two kaons and one pion. By using Monte Carlo signal events with the 4 models for the decay $\tau^- \to \phi\pi^-\nu_\tau$ (both non-resonance and resonance) and generic Monte Carlo τ events as background, we obtain the linear combination of these five variables that maximizes the separation for each model. In Fig. 1 b), we show the distribution of $\Delta_{\phi\pi\nu,\tau\tau}$ for signal events, $\tau^- \to \phi\pi^-\nu_\tau$, and background generic τ events for the model with a resonance at 1350 MeV/c^2.

After applying the multivariate linear discriminators, we obtain the mass spectra for each model (Fig. 2). Since there is no apparent ϕ signal found in the K^+K^- mass spectra in Fig. 2, the upper limit on the number of signal events at the 90% confidence level for each model is computed. The signal shape is assumed to be a Gaussian convoluted with a Breit-Wigner distribution. The mean and width of the ϕ meson Breit-Wigner distribution is given as 1.02 GeV/c^2 and 4 MeV/c^2 respectively, while the sigma of the convoluted Gaussian due to the detector resolution is 3 MeV/c^2. The background shapes are obtained from Monte Carlo samples of generic τ pair events and hadronic events after normalization to the cross sections. A maximum likelihood fit using Possion statistics is performed to obtain the number of signal events (N^{signal}) and the overall background normalization constant (α). Fig. 2 shows the resulting fits of the mass spectra for the decay mode $\tau^- \to \phi\pi^-\nu_\tau$.

The results for the decay $\tau^- \to \phi\pi^-\nu_\tau$ from the fits presented in Fig. 2 are given in Table I for each model, with χ^2 values of fits which are obtained from:

$$\chi^2 \equiv \sum_{i=1}^{\text{no. of bins}} \frac{(n_i^{data} - n_i^{signal} - \alpha n_i^{MC-back})^2}{n_i^{data} + (\sigma_i^{MC-back})^2}, \tag{1}$$

where n_i^{data} is the number of events in the ith data bin, n_i^{signal} is the number of the signal events in the ith bin from fitting, and $n_i^{MC-back}$ is the number of Monte Carlo background events from the generic τ's and hadronic events:

$$n_i^{MC-back} = n_i^{\tau} + n_i^{qq}. \tag{2}$$

Here n_i^{τ} (n_i^{qq}) is the number of events in the ith bin from the generic τ (hadronic) Monte Carlo sample after normalizing by luminosity, and $\sigma_i^{MC-back}$ is an error due to the finite Monte Carlo statistics on $n_i^{MC-back}$.

The efficiencies of the selection cuts estimated using Monte Carlo $\tau^- \to \phi\pi^-\nu_\tau$ events and the numbers of signal events at the 90% confidence level are obtained for the four models. The 90% confidence level upper limits for the branching fraction $\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau)$ and $\mathcal{B}(\tau^- \to \phi K^-\nu_\tau)$ are calculated using:

$$\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau) < \frac{N_{90}/\epsilon_{eff}}{2\sigma_\tau \mathcal{L}\mathcal{B}1\mathcal{B}(\phi \to K^+K^-)}. \tag{3}$$

Here, N_{90} is 90% confidence level upper limit on the number of signal events, ϵ_{eff} is the efficiency for selecting signal events, σ_τ is the τ pair cross section, taken as 0.91nb at CLEO energies, and $\mathcal{L}$ is the total luminosity. In addition, the 1-prong branching fraction, $\mathcal{B}1$ and the ϕ decay rate $\mathcal{B}(\phi \to K^+K^-)$ are obtained from the Particle Data Group as 0.8549 and 0.491, respectively [18].

In a separate calculation, the multivariate linear discriminators with five variables for the $\tau^- \to \phi K^-\nu_\tau$ analysis are obtained from generic τ pair events and two signal Monte Carlo samples: phase space and a resonance at 1650 MeV/c^2. After applying the discriminators for each model, we obtain the mass spectra shown in Fig. 3. Since again there is no apparent signal in either of these plots, we apply the same technique as in the study of the decay $\tau^- \to \phi\pi^-\nu_\tau$ to estimate the 90 % confidence upper limits. The results are given in Table II.

III. SYSTEMATIC ERRORS AND CHECKS

We consider the contributions to the systematic error from several sources. The uncertainty due to the luminosity estimate is taken as 1.5%, the error due to charged particle tracking is taken as 4%, and the error in the photon detection efficiency as 5%. We increase the total systematic error to 15% to include variations caused by the choice of cuts used in the analysis. The final upper limits are calculated by increasing the results obtained from Eq. 3 by 15% to include the contribution from the systematic errors. These results are given in Tables I and II. As a cross check we also perform a direct search for $\tau^- \to \phi\pi^-\nu_\tau$ and $\tau^- \to \phi K^-\nu_\tau$ using drift chamber dE/dx information to aid in the identification of charged kaons from ϕ decay. The results from this study are consistent although slightly less restrictive than the upper limits presented in Tables I and II.

IV. CONCLUSION

In order to search for the decays, $\tau^- \to \phi\pi^-\nu_\tau$ and $\tau^- \to \phi K^-\nu_\tau$, we have performed a multivariate analysis that exploits the kinematics of the decay. The limits obtained depend on the mass of the resonant state and vary between:

$$\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau) \quad < \quad 1.2 - 1.9 \times 10^{-4} \quad @ \quad 90\% \quad \text{C.L.} \tag{4}$$

$$\mathcal{B}(\tau^- \to \phi K^-\nu_\tau) \quad < \quad 5.4 - 6.7 \times 10^{-5} \quad @ \quad 90\% \quad \text{C.L.} \tag{5}$$

Our results for the decay $\tau^- \to \phi\pi^-\nu_\tau$ are a considerable improvement over the previous limit obtained using CVC and e^+e^- annihilation data. These limits are comparable to the "optimistic" theoretical estimate from the non-exotic model [5] but can not rule out the $\rho(1450)$ as the source of $\phi\pi$ events observed in [3].

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TABLE I. Estimated numbers of events, efficiencies and upper limits at 90% confidence level for the decay, $\tau^- \to \phi\pi^-\nu_\tau$, for each model.

Model	Phase Space	Resonance at 1350 MeV/c^2	Resonance at 1450 MeV/c^2	Resonance at 1650 MeV/c^2
N^{signal}	-16 ± 37	0.0 ± 23	-15 ± 23	-0.8 ± 31
$\chi^2(dof=23)$	12.5	34.2	38.5	15.1
N_{90}	46	37	27	48
ϵ_{eff}	12%	16%	8.2%	13%
Upper Limit	1.7×10^{-4}	1.0×10^{-4}	1.4×10^{-4}	1.6×10^{-4}
Upper Limit incl. Systematic Error	1.9×10^{-4}	1.2×10^{-4}	1.6×10^{-4}	1.8×10^{-4}

TABLE II. Estimated numbers of events, efficiencies, and upper limits at 90% confidence level for the decay, $\tau^- \to \phi K^-\nu_\tau$, for each model.

Model	Phase Space	Resonance at 1650 MeV/c^2
N^{signal}	-4.1 ± 15	-6.8 ± 16
$\chi^2(dof=23)$	9.8	13.6
N_{90}	22	21
ϵ_{eff}	16.1%	19.2%
Upper Limit	5.8×10^{-5}	4.7×10^{-5}
Upper Limit incl. Systematic Error	6.7×10^{-5}	5.4×10^{-5}

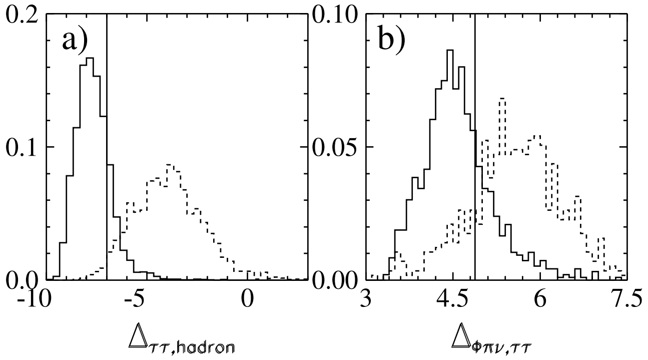

FIG. 1. Multivariate Linear Discriminators a) $\Delta_{\tau\tau,hadron}$ for 1 vs. 3 τ (solid line) events and hadronic (dotted line) events (normalized by luminosity) and b) $\Delta_{\phi\pi\nu,\tau\tau}$ for 1 vs 3 τ (dotted line) events and signal (solid line) events, $\tau^- \to \phi\pi^-\nu_\tau$, with a resonance at 1350 MeV/c^2 (normalized to unit area). The vertical lines show the cuts used in the analysis.

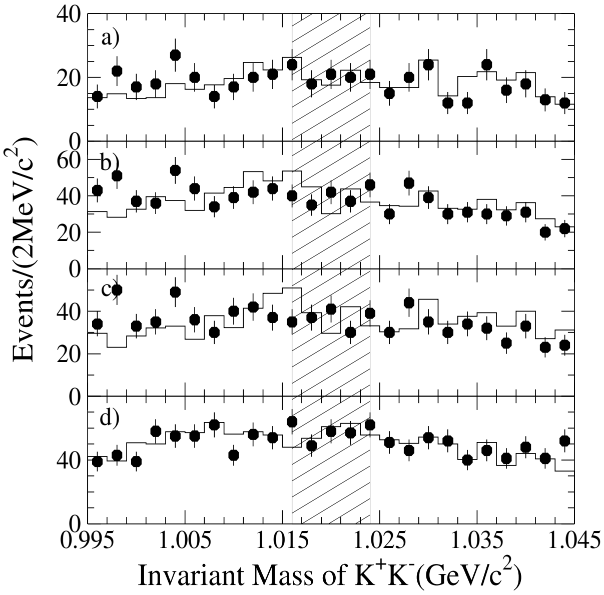

FIG. 2. Mass spectra from the decay $\tau^- \rightarrow \phi\pi^-\nu_\tau$ with a) phase space decay, and resonances at b) 1350 MeV/c^2, c) 1450 MeV/c^2, d) 1650 MeV/c^2. The shadowed area shows the signal region for the ϕ meson. The histograms are the Monte Carlo estimates of the signal plus background. The fitting procedure is described in the text.

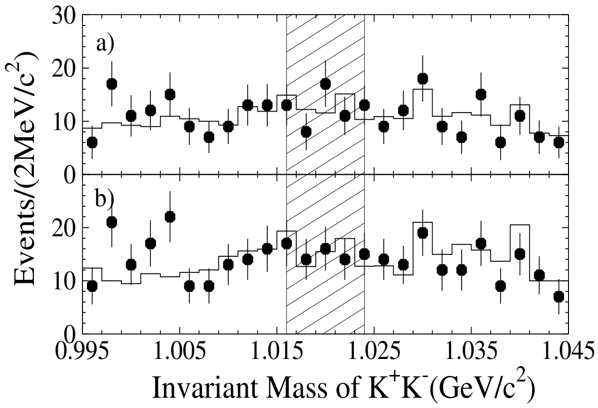

FIG. 3. The fits of the mass spectra from the decay $\tau^- \rightarrow \phi K^-\nu_\tau$ with a) phase space decay, and resonance at b) 1650 MeV/c^2. The shadowed area shows the signal region for the ϕ meson. The histograms are the Monte Carlo estimates of the signal plus background. The fitting procedure is described in the text.