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Search for ϕ mesons in τ lepton decay

P. Avery,[1] C. Prescott,[1] S. Yang,[1] J. Yelton,[1] G. Brandenburg,[2] R.A. Briere,[2] T. Liu,[2] M. Saulnier,[2] R. Wilson,[2] H. Yamamoto,[2] T. E. Browder,[3] F. Li,[3] J. L. Rodriguez,[3] T. Bergfeld,[4] B.I. Eisenstein,[4] J. Ernst,[4] G.E. Gladding,[4] G.D. Gollin,[4] I. Karliner,[4] M. Palmer,[4] M. Selen,[4] J.J. Thaler,[4] K.W. Edwards,[5] M. Ogg,[5] A. Bellerive,[6] D.I. Britton,[6] R. Janicek,[6] D.B. MacFarlane,[6] K.W. McLean,[6] P.M. Patel,[6] A.J. Sadoff,[7] R. Ammar,[8] P. Baringer,[8] A. Bean,[8] D. Besson,[8] D. Coppage,[8] N. Copty,[8] R. Davis,[8] N. Hancock,[8] S. Kotov,[8] I. Kravchenko,[8] N. Kwak,[8] S. Anderson,[9] Y. Kubota,[9] M. Lattery,[9] J.J. O'Neill,[9] S. Patton,[9] R. Poling,[9] T. Riehle,[9] A. Smith,[9] V. Savinov,[9] M.S. Alam,[10] S.B. Athar,[10] I.J. Kim,[10] Z. Ling,[10] A.H. Mahmood,[10] H. Severini,[10] S. Timm,[10] F. Wappler,[10] J.E. Duboscq,[11] R. Fulton,[11] D. Fujino,[11] K.K. Gan,[11] K. Honscheid,[11] H. Kagan,[11] R. Kass,[11] J. Lee,[11] M. Sung,[11] A. Undrus,[11*] C. White,[11] R. Wanke,[11] A. Wolf,[11] M.M. Zoeller,[11] B. Nemati,[12] S.J. Richichi,[12] W.R. Ross,[12] P. Skubic,[12] M. Wood,[12] M. Bishai,[13] J. Fast,[13] E. Gerndt,[13] J.W. Hinson,[13] D.H. Miller,[13] E.I. Shibata,[13] I.P.J. Shipsey,[13] M. Yurko,[13] L. Gibbons,[14] S.D. Johnson,[14] Y. Kwon,[14] S. Roberts,[14] E.H. Thorndike,[14] C.P. Jessop,[15] K. Lingel,[15] H. Marsiske,[15] M.L. Perl,[15] S.F. Schaffner,[15] R. Wang,[15] T.E. Coan,[16] V. Fadeyev,[16] I. Korolkov,[16] Y. Maravin,[16] I. Narsky,[16] V. Shelkov,[16] R. Stroynowski,[16] J. Staeck,[16] I. Volobouev,[16] J. Ye,[16] M. Artuso,[17] A. Efimov,[17] M. Gao,[17] M. Goldberg,[17] R. Greene,[17] D. He,[17] S. Kopp,[17] G.C. Moneti,[17] R. Mountain,[17] Y. Mukhin,[17] T. Skwarnicki,[17] S. Stone,[17] X. Xing,[17] J. Bartelt,[18] S.E. Csorna,[18] V. Jain,[18] S. Marka,[18] A. Freyberger,[19] D. Gibaut,[19] K. Kinoshita,[19] I.C. Lai,[19] P. Pomianowski,[19] S. Schrenk,[19] G. Bonvicini,[20] D. Cinabro,[20] B. Barish,[21] M. Chadha,[21] S. Chan,[21] G. Eigen,[21] J.S. Miller,[21] C. O'Grady,[21] M. Schmidtler,[21] J. Urheim,[21] A.J. Weinstein,[21] F. Würthwein,[21] D.M. Asner,[22] M. Athanas,[22] D.W. Bliss,[22] W.S. Brower,[22] G. Masek,[22] H.P. Paar,[22] J. Gronberg,[23] C.M. Korte,[23] D.J. Lange,[23] R. Kutschke,[23] S. Menary,[23] R.J. Morrison,[23] S. Nakanishi,[23] H.N. Nelson,[23] T.K. Nelson,[23] C. Qiao,[23] J.D. Richman,[23] D. Roberts,[23] A. Ryd,[23] H. Tajima,[23] M.S. Witherell,[23] R. Balest,[24] B.H. Behrens,[24] K. Cho,[24] W.T. Ford,[24] M. Lohner,[24] H. Park,[24] P. Rankin,[24] J. Roy,[24] J.G. Smith,[24] J.P. Alexander,[25] C. Bebek,[25] B.E. Berger,[25] K. Berkelman,[25] K. Bloom,[25] D.G. Cassel,[25] H.A. Cho,[25] D.M. Coffman,[25] D.S. Crowcroft,[25] M. Dickson,[25] P.S. Drell,[25] D.J. Dumas,[25] R. Ehrlich,[25] R. Elia,[25] P. Gaidarev,[25] R.S. Galik,[25] B. Gittelman,[25] S.W. Gray,[25] D.L. Hartill,[25] B.K. Heltsley,[25] C.D. Jones,[25] S.L. Jones,[25] J. Kandaswamy,[25] N. Katayama,[25] P.C. Kim,[25] D.L. Kreinick,[25] T. Lee,[25] Y. Liu,[25] G.S. Ludwig,[25] J. Masui,[25] J. Mevissen,[25] N.B. Mistry,[25] C.R. Ng,[25] E. Nordberg,[25] J.R. Patterson,[25] D. Peterson,[25] D. Riley,[25] A. Soffer,[25] and C. Ward[25]

(CLEO Collaboration)

[1] *University of Florida, Gainesville, Florida 32611*

[2]*Harvard University, Cambridge, Massachusetts 02138*
[3]*University of Hawaii at Manoa, Honolulu, HI 96822*
[4]*University of Illinois, Champaign-Urbana, Illinois, 61801*
[5]*Carleton University, Ottawa, Ontario K1S 5B6 and the Institute of Particle Physics, Canada*
[6]*McGill University, Montréal, Québec H3A 2T8 and the Institute of Particle Physics, Canada*
[7]*Ithaca College, Ithaca, New York 14850*
[8]*University of Kansas, Lawrence, Kansas 66045*
[9]*University of Minnesota, Minneapolis, Minnesota 55455*
[10]*State University of New York at Albany, Albany, New York 12222*
[11]*Ohio State University, Columbus, Ohio, 43210*
[12]*University of Oklahoma, Norman, Oklahoma 73019*
[13]*Purdue University, West Lafayette, Indiana 47907*
[14]*University of Rochester, Rochester, New York 14627*
[15]*Stanford Linear Accelerator Center, Stanford University, Stanford, California, 94309*
[16]*Southern Methodist University, Dallas, Texas 75275*
[17]*Syracuse University, Syracuse, New York 13244*
[18]*Vanderbilt University, Nashville, Tennessee 37235*
[19]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[20]*Wayne State University, Detroit, Michigan 48202*
[21]*California Institute of Technology, Pasadena, California 91125*
[22]*University of California, San Diego, La Jolla, California 92093*
[23]*University of California, Santa Barbara, California 93106*
[24]*University of Colorado, Boulder, Colorado 80309-0390*
[25]*Cornell University, Ithaca, New York 14853*
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Abstract

We report results from a direct search for $\tau^- \to \phi h^- \nu_\tau$ ($h^- = \pi^-$or K^-) using 3.1 fb^{-1} of data collected with the CLEO II detector. We find model-dependent upper limits on the branching fractions in the range: $\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau) < (1.2-2.0)\times 10^{-4}$ and $\mathcal{B}(\tau^- \to \phi K^-\nu_\tau) < (5.4-6.7)\times 10^{-5}$ at 90% confidence level.

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*Permanent address: BINP, RU-630090 Novosibirsk, Russia

I. INTRODUCTION

A measurement of the decay $\tau^- \to \phi\pi^-\nu_\tau$ [1] is of interest as it may provide 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 1480 MeV/c^2 and $J^{PC} = 1^{--}$ [3,4] which decays into $\phi\pi$. Building on the work of Ref. [5], Eidelman and Ivanchenko [6] estimate the branching fraction of $\tau^- \to \phi\pi^-\nu_\tau$ assuming that the $C(1480)$ is actually the $\rho(1450)$. This non-exotic assumption for the $C(1480)$ yields a "most optimistic" branching fraction of $\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau) = 0.02\%$. However, the branching fraction will be much smaller if the resonance is an exotic state. A more conventional analysis [7] based on vector-meson dominance (VMD) and the measurement of $\mathcal{B}(\tau^- \to \omega\pi^-\nu_\tau)$ predicts $\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau) = (1.20 \pm 0.48) \times 10^{-5}$. The authors also point out that this decay mode provides a clean environment to study OZI [8] suppression. It is also possible to estimate the branching ratio for this process, independent of the assumed intermediate resonance using the conserved vector current hypothesis (CVC) and data from e^+e^- annihilations. The upper limits on the cross section of the reaction $e^+e^- \to \phi\pi^0$ from Ref. [9–11] imply an upper limit of 0.06% [12] for $\tau^- \to \phi\pi^-\nu_\tau$.

The first search for $\tau^- \to \phi\pi^-\nu_\tau$ was performed by the CLEO experiment where a preliminary 90% confidence level upper limit of $\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau) < 2.6 \times 10^{-4}$ was reported [13]. Recently the ARGUS collaboration obtained a 90% confidence level upper limit of $\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau) < 3.5 \times 10^{-4}$ [14], consistent with the CLEO result. In this letter we update the CLEO result and investigate several models for the decay $\tau^- \to \phi\pi^-\nu_\tau$.

We also search for the decay $\tau^- \to \phi K^-\nu_\tau$ using a similar technique and present the first upper limits on the branching fraction for this decay mode. Although this decay mode is OZI allowed, its branching fraction is expected to be small due to Cabibbo and phase space supression. For example, scaling the branching fraction of the Cabibbo allowed analog reaction $\tau^- \to K^*K^-\nu_\tau$ [15] by $tan^2\theta_c$ (θ_c=Cabibbo angle) and the ratio of phase space of the two reactions yields $\mathcal{B}(\tau^- \to \phi K^-\nu_\tau) = 2 \times 10^{-5}$. However, a more careful analysis [16] shows that this branching fraction is very sensitive to the mixing of the SU(3) octet and singlet states and deviations from nonet symmetry of vector mesons.

II. ANALYSIS

This analysis uses 3.1 fb^{-1} of data collected with the CLEO II detector [17] at the Cornell Electron Storage Ring (CESR). The data sample 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 intothree charged tracks (1 vs 3 topology). We search these events for $\phi \to K^+K^-$ by forming the invariant mass of oppositely charged tracks, assuming the kaon mass for each track. We make tight requirements on the kinematic variables involved in the production and decay of the ϕ.

To select a τ pair sample with the 1 vs 3 charged track topology, all events are required to have 4 charged tracks with zero net charge and total missing mass squared [18] greater than zero. To remove radiative QED background (mostly Bhabhas), events with 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 $m_{e^+e^-} \leq 50\ \mathrm{MeV}/c^2$.

In order to distinguish τ-pair events from hadronic background ($e^+e^- \to q\bar{q}$) we use a standard statistical method, the multivariate linear discriminant technique [19,20]. For this analysis, six kinematical variables are combined in a linear fashion to form the discriminant $\Delta_{\tau\tau,q\bar{q}}$. The variables used are the transverse momentum and missing mass in the event, the invariant mass and energy on the 1 and 3-prong side. In Fig. 1 a), we show the distribution of $\Delta_{\tau\tau,q\bar{q}}$ for Monte Carlo τ-pairs [21] and hadronic continuum events. For this analysis we require $\Delta_{\tau\tau,q\bar{q}} \leq -7$. This retains 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, $B\bar{B}$ 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 [22]. For the models with an intermediate resonant state, we generate samples of τ pair events, in which one τ decays into a ν_τ and a resonant state that decays into $\phi\pi$, while the other τ decays into one charged particle. Because we have little information on the resonant 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 [23]. 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 $\phi \to K^+K^-$, the following conditions are imposed on the 3-prong side of each candidate event: i) The momentum of each kaon candidate track must satisfy $0.9 \leq |\bar{\mathbf{p}}_K| \leq\ 2.4\ \mathrm{GeV}/c$. ii) The angle between the two kaon candidates in the laboratory frame must be $\leq$0.2 radians. In addition, there must be no more than one unmatched photon candidate with energy $\geq$ 100 MeV.

Monte Carlo studies indicate that at this stage of the analysis, most events will be background 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 variables are 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 four 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. 1b), 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 Poisson statistics is performed to obtain the number of signal events (N^{signal}) and the overall background normalization constant (α). In Fig. 2 we show the resulting fits of the mass spectra for the decay mode $\tau^- \rightarrow \phi\pi^-\nu_\tau$.

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

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

Here n_i^{τ} ($n_i^{q\bar{q}}$) 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 $\tau^- \rightarrow \phi\pi^-\nu_\tau$ 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 $\mathcal{B}(\tau^- \rightarrow \phi\pi^-\nu_\tau)$ and $\mathcal{B}(\tau^- \rightarrow \phi K^-\nu_\tau)$ are calculated using:

$$\mathcal{B}(\tau^- \rightarrow \phi\pi^-\nu_\tau) < \frac{N_{90}/\epsilon_{eff}}{2\sigma_\tau \mathcal{L}\mathcal{B}_1\mathcal{B}(\phi \rightarrow K^+K^-)}. \tag{3}$$

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 $\mathcal{B}(\phi \rightarrow K^+K^-)$ are taken from Ref. [15].

In a separate calculation, the multivariate linear discriminators with five variables for the $\tau^- \rightarrow \phi K^-\nu_\tau$ 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 used in the study of $\tau^- \rightarrow \phi\pi^-\nu_\tau$ 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 1.5%, the error due to modeling the charged particle tracking is 4%, and the error in the photon detection efficiency is 5%. We increase the total systematic error to 15% taking into account the choice of cuts, fitting procedure, and modeling of the background. 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 larger 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:

$$\mathcal{B}(\tau^- \to \phi\pi^-\nu_\tau) \quad < \quad 1.2 - 2.0 \times 10^{-4} \quad @ \quad 90\% \quad \text{C.L.} \tag{4}$$

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

Our results for the decay $\tau^- \to \phi\pi^-\nu_\tau$ are a considerable improvement over the previous limits obtained using CVC and/or e^+e^- annihilation data. These limits are comparable to the "optimistic" theoretical estimate from the non-exotic model [6] but about an order of magnitude higher than a VMD [7] calculation. Results from the first search for $\tau^- \to \phi K^-\nu_\tau$ are also presented. These upper limits are consistent with expectations from Cabibbo and phase space suppression.

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[23] For the resonance state at 1450 MeV/c^2, we use the width of $\rho(1450)$ from the Particle Data Group [15], in order to check the non-exotic resonance proposed in Ref. [5].

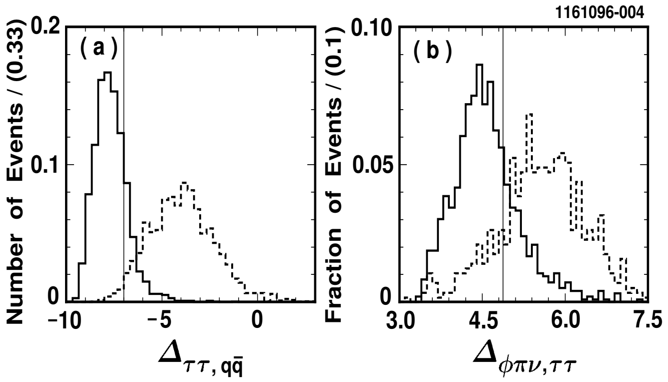

FIG. 1. Multivariate Linear Discriminators a) $\Delta_{\tau\tau,q\bar{q}}$ for 1 vs 3 τ (solid line) and hadronic (dotted line) events (normalized by luminosity) and b) $\Delta_{\phi\pi\nu,\tau\tau}$ for 1 vs 3 τ (dotted line) and signal (solid line) events, $\tau^- \to \phi\pi^-\nu_\tau$, with a resonance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

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
$\epsilon_{eff}(\%)$	12	16	8.2	13
Upper Limit(10^{-4})	1.7	1.0	1.4	1.6
Upper Limit with Systematic Error (10^{-4})	2.0	1.2	1.7	1.8

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
$\epsilon_{eff}(\%)$	16.1	19.2
Upper Limit (10^{-5})	5.9	4.7
Upper Limit with Systematic Error (10^{-5})	6.7	5.4

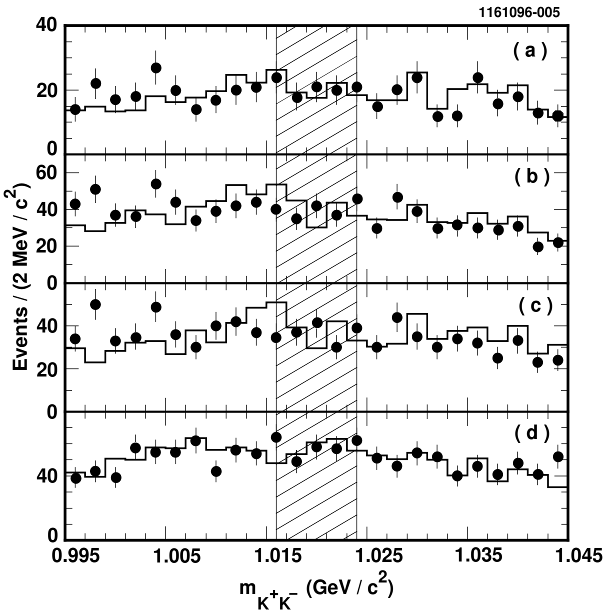

FIG. 2. Mass spectra from the decay $\tau^- \to \phi\pi^-\nu_\tau$ with a) phase space decay, and resonances at b) 1350 MeV/c^2, c) 1450 MeV/c^2, d) 1650 MeV/c^2. The shaded area shows the signal region for the ϕ meson. The histograms are the Monte Carlo estimates of the signal plus background. The fitting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

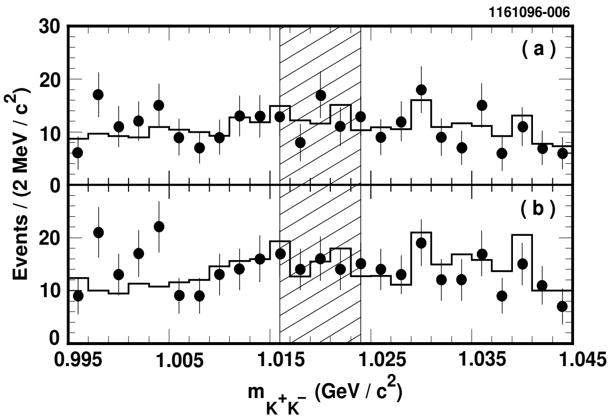

FIG. 3. The fits of the mass spectra from the decay $\tau^- \to \phi K^-\nu_\tau$ with a) phase space decay, and resonance at b) 1650 MeV/c^2. The shaded area shows the signal region for the ϕ meson. The histograms are the Monte Carlo estimates of the signal plus background. The fitting procedure is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