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Observation of Tau Decays with Two Neutral Kaons

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Abstract

We report on the observation of the decay $\tau^- \to \nu_\tau K^0 \bar{K^0} \pi^-$ in 3.11 fb^{-1} of data taken with the CLEO II detector at the Cornell Electron Storage Ring. Both K^0 mesons are detected through their decays via $K_S \to \pi^+\pi^-$. Preliminary results on the branching fraction and on the resonant sub-structure are presented. In particular, we find $B(\tau^- \to \nu_\tau K^0 \bar{K^0} \pi^-) = 0.083 \pm 0.017 \pm 0.017\,\%$. We also comment on the sensitivity of the $KK\pi$ invariant mass spectrum to a non-zero tau-neutrino mass.

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I. INTRODUCTION

Tau lepton decays of the type $\tau^- \to \nu_\tau[KK\pi]^-$ have been known to exist [1] for nearly a decade. However, due to the small decay width and difficulties associated with identifying kaons, little information is presently available for these decays. In this paper, we report on the observation of $KK\pi$ decays where both kaons are neutral, based on 3.11 fb^{-1} of e^+e^- annihilation data collected with the CLEO-II detector operating at the Cornell Electron Storage Ring ($\sqrt{s} \sim 10.6$ GeV). We detect the kaons through their decays to $\pi^+\pi^-$, which occur at points spatially separated from the e^+e^- interaction point (IP) owing to the finite K_S lifetime. In companion papers submitted to this conference [2,3], studies of tau decays containing one K_S are presented.

In tau decay, production of the $[KK\pi]^-$ system can occur through either the vector or axial-vector non-strange weak hadronic current [4,5]. When four $\tau^- \to \nu_\tau K^+K^-\pi^-$ events were identified by the DELCO experiment [1] in 1985, it was suggested [4] that such a decay might arise through production (via the vector current) of the ρ', which could decay to K^*K. A recent chiral perturbation theory inspired model [5] holds that production of an axial-vector state (possibly the $a_1(1260)$) dominates, where $KK\pi$ occurs via K^*K or $\rho\pi$ intermediate states (in the latter, $\rho \to K\bar{K}$ through its high-mass tail).

While the dynamics governing $KK\pi$ decays merit study, the primary interest in these decays lies in their utility for constraining the mass of the tau neutrino. Because these decays are greatly phase-space suppressed, the $KK\pi$ mass spectrum may be sensitive to a non-zero tau neutrino mass, as events are likely to populate the region near the kinematic endpoint $M_\tau - M_{\nu_\tau}$. Indeed, from their four events, DELCO derived the most stringent limit on M_{ν_τ} at that time [1]. These data are insufficient to determine whether $KK\pi$ is more or less sensitive than the also-rare five-pion final states (BR$\sim 0.1\%$) which have so far provided the best limits (31 and 32.6 MeV/c^2) on M_{ν_τ} [6,7].

Although $\tau^- \to \nu_\tau[KK\pi]^-$ can appear in three charge combinations: $K^-K^+\pi^-$, $K^-K^0\pi^0$, and $K^0\bar{K}^0\pi^-$, experiments have so far focussed on the all-charged mode. Like DELCO, TPC [8] also observed four such events. Despite having limited π^-/K^- separation, CLEO-1.5 [9] and ARGUS [10] have observed events with reconstructed $K^{*0} \to K^+\pi^-$ decays, but significant backgrounds degrade the potential for stringent neutrino mass limits from these samples. The measured branching fractions are listed below:

$$\begin{aligned}
B(\tau^- \to \nu_\tau K^-K^+\pi^-) &= 0.22^{+0.17}_{-0.11}\,\% && \text{(DELCO)},\\
B(\tau^- \to \nu_\tau K^-K^+\pi^-) &= 0.15^{+0.09}_{-0.07}\,\% && \text{(TPC)},\\
B(\tau^- \to \nu_\tau K^-K^+\pi^-) &= 0.21 \pm 0.09\,\% && \text{(CLEO 1.5)},\\
B(\tau^- \to \nu_\tau K^-K^+\pi^-) &= 0.12 \pm 0.04\,\% && \text{(ARGUS -- prelim.)},
\end{aligned}$$

where the CLEO and ARGUS values are derived from measurements of $B(\tau^- \to \nu_\tau K^-K^{*0}X^0)$, if one assumes there are no unseen neutrals and that K^*K saturates the $KK\pi$ final state.

New results from ALEPH [11] and CLEO-II [2] show indications of $\tau^- \to \nu_\tau K^-K^0\pi^0$ signals:

$$\begin{aligned}
B(\tau^- \to \nu_\tau K^-K^0\pi^0) &= 0.05 \;\; \pm 0.05 \;\; \pm 0.01 \;\; \% && \text{(ALEPH)},\\
B(\tau^- \to \nu_\tau K^-K^0\pi^0) &= 0.129 \pm 0.050 \pm 0.032\,\% && \text{(CLEO II -- prelim.)}.
\end{aligned}$$

In this paper, we focus on the decay $\tau^- \to \nu_\tau K^0 \bar{K}^0 \pi^-$, where both kaons appear as K_S mesons decaying to $\pi^+\pi^-$ pairs. Studying this channel has the advantage that $K_S \to \pi^+\pi^-$ leaves an unambiguous signature by virtue of the flight distance of the K_S. Hence, fake kaon backgrounds are small. The disadvantages are that only 12% of $K^0\bar{K}^0\pi^-$ events result in this particular decay sequence, and that reconstruction of the K_S decays results in some loss of efficiency. Below we describe the measurement of the branching fraction for this decay. We comment on the potential for constraining M_{ν_τ} at the end of this note.

II. BRANCHING FRACTION DETERMINATION

We determine the $\tau^- \to \nu_\tau K^0 \bar{K}^0 \pi^-$ branching fraction by counting events where the $K_S K_S \pi^-$ system is recoiling against a τ^+ decay (the 'tag') to one charged particle plus neutrino(s), but no other neutrals (*ie.*, $\nu e \nu$, $\nu \mu \nu$, $\nu \pi$, νK final states).[1] The branching ratio is normalized to the number of produced tau-pairs, $N_{\tau\tau} = 2.84 \times 10^6$, determined from the tau-pair production cross section and the integrated luminosity (known from studies of $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \gamma\gamma$). The event selection criteria are made sufficiently loose as to obtain a large, but mostly background-free, event sample. The major sources of systematic error arise from possible non-tau backgrounds and uncertainties in reconstructing $K_S \to \pi^+\pi^-$ decays.

A. Event Selection

The CLEO-II detector is a solenoidal spectrometer and calorimeter [13]. Events are selected which possess a '1–5' topology, where the most isolated track has momentum > 250 MeV/c, and projects to the barrel region of the detector, $|\cos\theta| < 0.81$, where θ is the polar angle relative to the beam axis. Each of the remaining 5 tracks must be separated from the isolated track by $> 105°$, have at least 100 MeV/c of transverse momentum, and lie within the angular range $|\cos\theta| < 0.90$.

To eliminate radiative Bhabha events, the total energy in the calorimeter must be less than 85% of the center-of-mass energy $E_{\rm cm}$. Bhabhas, two-photon and other hadronic backgrounds are suppressed by requiring that the missing momentum determined from the tracks must point into the detector ($|\cos\theta_{\rm missing}| < 0.9$). Finally the event is separated into two hemispheres defined by the plane perpendicular to the 5-prong momentum vector, and events with unmatched showers are vetoed according to their energy and location. In the 1-prong hemisphere, only one unmatched shower may have energy above 100 MeV, and its energy must be less than 200 MeV. In the 5-prong hemisphere, there may be any number of unmatched showers, but none may have more than 500 MeV of energy.

[1]Note that although they have the same 1–5 charged-track topology as in the recent CLEO-II neutrino mass [7] and 5-prong branching ratio [12] studies, $K_S K_S \pi^-$ events were effectively excluded from those analyses, since all six tracks were required to project to a common vertex.

B. K_S Reconstruction

The reconstruction of two K_S decays in events passing the above criteria eliminates most backgrounds from tau and non-tau processes. For consistency, the procedures used and cuts applied are similar to what has been done in the CLEO-II analyses of tau decays with one K_S [2,3]. Specifically, two oppositely charged tracks which intersect in the transverse (x-y) plane relative to the beam axis (z) are considered as K_S candidates if:

1. Both tracks are in the 5-prong hemisphere;
2. The K_S decay vertex is separated from the beam spot in the radial direction by more than 3 mm;
3. The distance between the tracks in z at the x-y intersection point is less than 15 mm;
4. The distance of closest approach to the IP (in the x-y plane) of the inferred K_S trajectory is less than 2 mm.

Finally, track-pairs with at least one well-identified electron may be rejected as possible converted photons, following critera based on the polar angles of the tracks and the spatial separation in x-y of the two tracks at the point where their tangents are parallel.

C. Final Event Sample

Of the events containing two distinct secondary vertices as defined above, we consider those where both vertices have invariant masses consistent with the K_S mass. We designate the mass range $0.480 < M_{\pi\pi} < 0.510$ GeV/c^2 as the K_S signal region and use events with $0.460 < M_{\pi\pi} < 0.475$ and $0.515 < M_{\pi\pi} < 0.530$ for a K_S sideband region to estimate the background from events with photon conversions or spurious secondary vertices. Plots of $M_{\pi\pi}$ versus $M_{\pi\pi}$ for events with $M_{K_S K_S \pi} < 1.8$ GeV/c^2 which pass all other cuts are shown in Figure 1. Two events from the cluster in the K_S signal region are depicted schematically in Figure 2.

In Figure 3, $M_{K_S K_S \pi}$ is plotted for events in the K_S signal and sideband regions. There are 38 data events below M_τ in the K_S signal region, of which 5.0 ± 2.2 are attributable to tau background based on the population of events in the K_S sideband regions. Six events (plus two in the K_S sideband regions) have masses above M_τ, probably due to hadronic backgrounds.

We have looked for indications of resonant substructure in these events. In Figure 4, we plot the invariant masses of the $K_S\pi$ combinations (two entries per event). Here the Monte Carlo (described below) and data agree, providing evidence for a $K^*(892)$ component. A 'Dalitz plot' of the two possible $K_S\pi$ masses is shown for data and Monte Carlo separately in Figure 5.

D. Detection Efficiency and Tau Backgrounds

The detection efficiency and backgrounds from tau decays are determined from studies of Monte Carlo samples generated using the `KORALB` tau-pair production and decay programs [14] and the `GEANT` [15] detector simulation package. The model used to simulate $\tau^- \to \nu_\tau K^0 \bar{K}^0 \pi^-$ is that of Decker *et al.*, as noted in Section I (see Ref. [5]). The overall efficiency, including all relevant branching fractions, was found to be $0.61 \pm 0.03\,(\mathrm{stat.})\,\%$; this corresponds to an efficiency of $10.6 \pm 0.5\,\%$ for detecting $\nu_\tau K_S K_S \pi^-$ decays, with both K_S's decaying to $\pi^+\pi^-$, recoiling against one of the four tag modes. As seen in Figure 1, backgrounds from tau decays to final states other than $K_S K_S \pi^-$ are expected to be negligible after K_S sideband subtraction.[2]

E. Non-Tau Backgrounds

As noted in Section II C, six events in the data have masses above M_τ, indicating possible contamination from multihadronic ($e^+e^- \to q\bar{q}$) processes. To study such backgrounds, we have analyzed a sample of 8.8×10^6 $q\bar{q}$ Monte Carlo events (representing $\sim$ 80% of the luminosity of the data), in which two events (plus one K_S sideband event) satisfy all cuts. We have also examined both data and Monte Carlo with looser and tighter cuts applied. From these studies, we estimate a contamination of 4 ± 4 events from this source.

The presence of non-tau backgrounds will spoil the sensitivity of this sample for M_{ν_τ} studies. However, background-free samples can be attained after application of more stringent cuts to remove events with excess energy deposition in the calorimeter or in regions in phase space preferentially populated by hadronic events, at a cost of lower detection efficiency.

F. Results for the Branching Ratio

Based on the 29.0 ± 7.7 events in the data after background subtractions, and the efficiencies determined from the Monte Carlo samples, we determine the branching ratio for $\tau^- \to \nu_\tau K^0 \bar{K}^0 \pi^-$ to be $0.083 \pm 0.017\,(\mathrm{stat.}) \pm 0.017\,(\mathrm{syst.})\,\%$. The systematic error is discussed in the following section.

III. SYSTEMATIC ERRORS

The estimated systematic errors entering the measurement of the $\tau^-\nu_\tau \to K^0 \bar{K}^0 \pi^-$ branching fraction are compiled in Table I. The dominant errors, due to uncertainties in detection efficiency and background estimation, are discussed below.

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[2]We have assumed that possible contributions from final states not simulated, such as $K_S K_S \pi^- \pi^0$, are negligible due to the severity of the phase-space suppression of such channels.

TABLE I. Systematic Errors on the $K^0\bar{K}^0\pi^-$ Branching Fraction.

Source	Uncertainty	
	Relative (%)	Absolute (%)
Monte Carlo Statistics	4.9	0.004
Decay Model	2.0	0.002
Track-finding Efficiency	9.3	0.008
K_S-finding Efficiency	10.0	0.008
Tau Backgrounds	5.0	0.005
Non-tau-pair Backgrounds	14.0	0.012
Number of Tau-pairs	1.4	0.001
Total Systematic Error	20.9	0.017

A. Uncertainties in Detection Efficiency

As previously noted, we rely on the Monte Carlo to provide an accurate estimate of the detection efficiency for the $K_SK_S\pi$ decays. First, the performance of the track-finding algorithm on Monte Carlo events must mimic that in the data. Studies of well-identified lepton vs. $3\pi^\pm$ tau samples in which at least two of the three pions are found show agreement between Monte Carlo and data to better than 0.5% per track. The more complicated topology of $K_SK_S\pi$ events, plus the K_S mass requirements (elaborated on below), leads us to conservatively assign a 2.0% error per track for pions from a K_S decay.

Second, once the tracks are found, the vertex-finding algorithm must operate similarly on Monte Carlo and data. Vertexing requires that the $\pi^+\pi^-$ tracks must not only be found but also be well-measured, such that all cuts (including the mass cut) are satisfied. Comparisons of Monte Carlo and data for distributions of vertexing quantities show good agreement, but are limited by the statistics of the data. We have also measured the $K^0\bar{K}^0\pi^-$ branching fraction from a sample of lepton-tagged events in which only one of the K_S decays is required to be reconstructed. This approach has twice the efficiency – but admits considerable tau ($11\pm5\%$) and non-tau backgrounds ($21\pm10\%$). The $K^0\bar{K}^0\pi^-$ branching fraction determined in this way is $0.091\pm0.026\%$. Based on these results plus the ratio of K_S yields in hadronic events as determined from track-pairs with or without secondary vertex requirements, we assign an error on K_S-finding of 5% per K_S.

Finally, the detection efficiency is not constant across the $KK\pi$ mass spectrum, higher by $\sim$ 50% at $M_{KK\pi}$ = 1.8 GeV/c^2 than at $M_{KK\pi}$ = 1.2 GeV/c^2. This suggests that proper modelling of the decay may play an important role in correctly estimating the overall efficiency. In fact, in Fig. 3, we see that the $KK\pi$ mass spectrum in the data is shifted relative to the Monte Carlo simulation. We have estimated the effect of this shift on the branching fraction to be less than 2%, by computing the branching fraction using a mass-dependent efficiency correction.

B. Uncertainties in Background Estimation

The uncertainty in the estimated hadronic background fraction is based on several tests. First, of the selected events, 15 ± 5 have well-identified leptons recoiling against the $K_S K_S \pi$ candidate. From these lepton-tagged events, the branching fraction is found to be $0.072 \pm 0.022\,(\text{stat.})\,\%$, assuming no backgrounds are present in this sample. Second, as noted earlier, the event selection was made intentionally loose in this analysis, so as to retain high efficiency. The application of tighter cuts preferentially removes events with $M_{K_S K_S \pi} > M_\tau$, and the corresponding branching fraction determinations are consistent to within 14%. Finally, the $q\bar{q}$ Monte Carlo is able to reproduce the shape and yield of high-mass events (to within a factor of two) in samples where only one K_S is required to be reconstructed. From these studies, we take the uncertainty on the hadronic background fraction to be 100% of itself.

IV. CONCLUSIONS AND DISCUSSION

To summarize, we have identified 38 events consistent with the process $\tau^- \rightarrow \nu_\tau K_S K_S \pi^-$, where the K_S's are identified by their decays to charged-pion pairs, of which 9 ± 5 events are expected to be from tau and hadronic backgrounds. We measure a preliminary branching ratio of

$$B(\tau^- \rightarrow \nu_\tau K^0 \bar{K}^0 \pi^-) = 0.083 \pm 0.017\,(\text{stat.}) \pm 0.017\,(\text{syst.})\,\%,$$

where the systematic error is dominated by uncertainties in non-tau backgrounds and K_S finding.[3]

This represents the first observation of the $K^0 \bar{K}^0 \pi$ channel, a final state which may have promise for constraining M_{ν_τ}. We are in the process of studying the $K_S K_S \pi$ mass spectrum and possible substructure in $M_{K_S \pi}$. We find that the $KK\pi$ mass spectrum is harder than that resulting from the model of Ref. [5], but that the $M_{K_S \pi}$ spectrum (most notably, the $K^*(892)$ component) is well-reproduced by this model. From inspection of the raw $M_{K_S K_S \pi}$ spectrum shown in Fig. 3, it is evident that this sample will not provide a competitive limit on M_{ν_τ}. However, the mass spectrum is similar in shape to that observed in the 5-pion samples recently used for M_{ν_τ} studies [6,7], so larger data samples may be useful in this regard. Furthermore, should future detectors at CESR, SLAC and KEK have sufficient charged kaon identification capabilities, the $K^- K^+ \pi^-$ channel may be more useful still, due to the larger attainable event yield.

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[3] We note that this result is based on the assumption that the probability for the $K^0 \bar{K}^0 \pi^-$ system to appear as $K_S K_S \pi^-$ is 25%. This may not be the case if, for example, $K^0 \bar{K}^0 \pi^-$ occurs through an $X^0_{\text{CP}} \pi^-$ intermediate state in which X^0 represents a CP-eigenstate (*i.e.*, a ϕ or ρ^0 meson).

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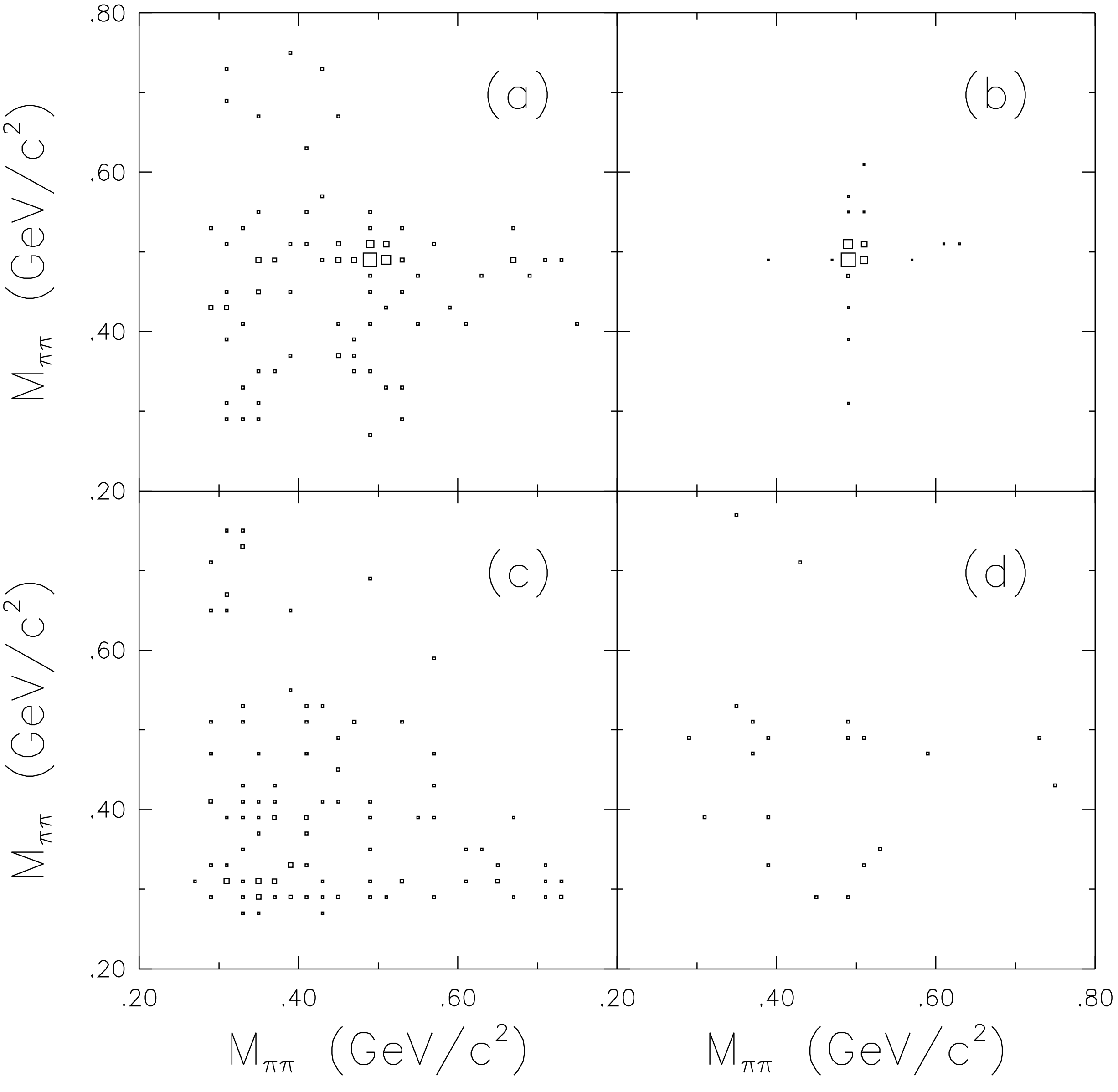

FIG. 1. Plots of $M_{\pi\pi}$ versus $M_{\pi\pi}$ for events passing all other selection criteria are shown for (a) data events, (b) $K_SK_S\pi$ signal Monte Carlo events, (c) generic tau-pair Monte Carlo events (excluding $K_SK_S\pi$), and (d) $e^+e^- \to q\bar{q}$ Monte Carlo events (representing ~ 2.5 fb^{-1} of data).

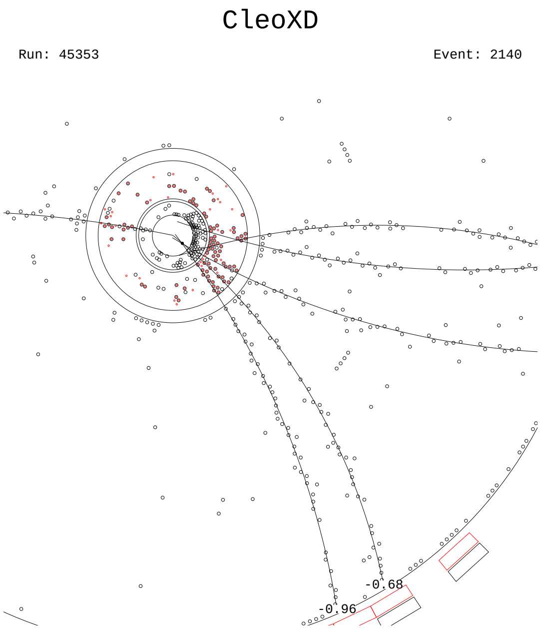

FIG. 2. Schematic depictions of two $\tau^- \to \nu_\tau K^0 \bar{K^0} \pi^-$ candidate events.

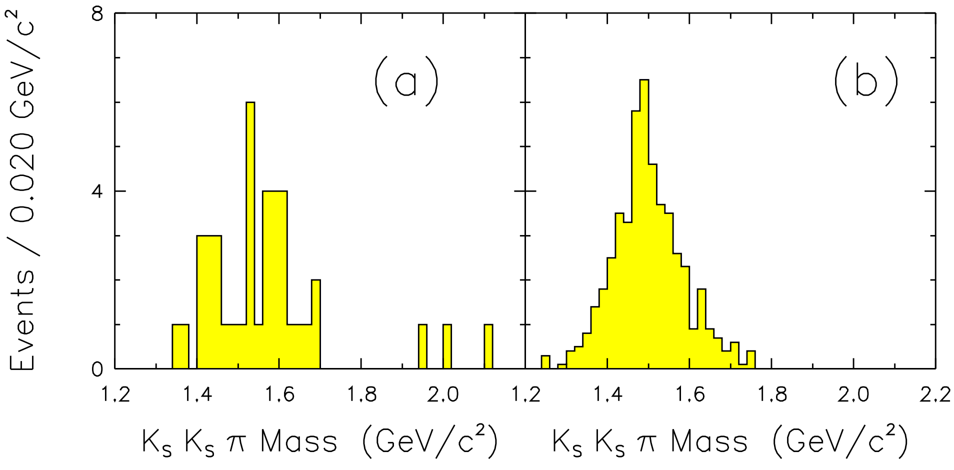

FIG. 3. Plots of $M_{K_S K_S \pi}$ for events passing all other selection criteria are shown for (a) data and (b) $K_S K_S \pi$ Monte Carlo events, where both $\pi^+\pi^-$-pairs lie in the K_S signal region. Three additional events in the data have masses above 2.2 GeV/c^2.

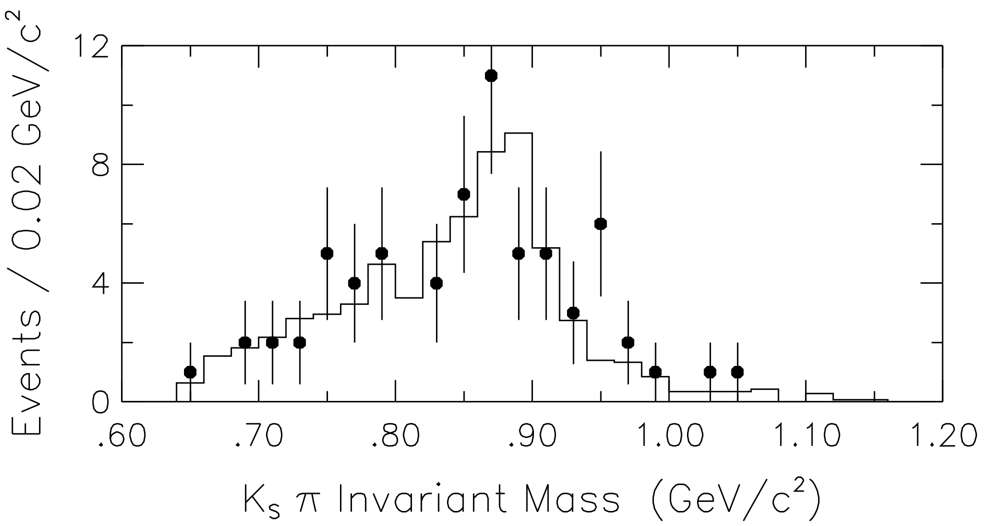

FIG. 4. $K_S\pi^-$ mass spectrum (two entries per event) for $\tau^- \to \nu_\tau K_S K_S \pi^-$ candidates in the data (points) and signal Monte Carlo (histogram).

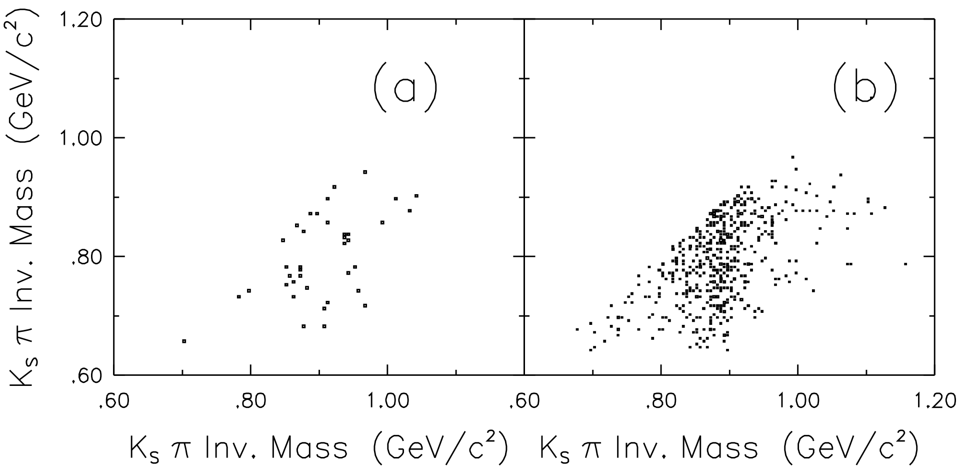

FIG. 5. Plots of $M_{K_S\pi}$(low) versus $M_{K_S\pi}$(high) for events passing all selection criteria are shown for (a) data and (b) signal Monte Carlo.