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Measurement of the branching fractions for $\tau^- \to \pi^- K_S \pi^0 \nu_\tau$ and $\tau^- \to K^- K_S \pi^0 \nu_\tau$

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Abstract

We present a measurement of the branching fractions for $\tau^- \to \pi^- K_S \pi^0 \nu_\tau$ and $\tau^- \to K^- K_S \pi^0 \nu_\tau$ decays using a data sample containing $616{\times}10^6$ $\tau^+\tau^-$ pairs accumulated with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The branching fractions for $\tau^- \to \pi^- K_S \pi^0 \nu_\tau$ and $\tau^- \to K^- K_S \pi^0 \nu_\tau$ are found to be $(0.192 \pm 0.002 \pm 0.008)\%$ and $(0.074 \pm 0.001 \pm 0.004)\%$, respectively.

Keywords: tau, semihadronic decay, branching fraction

1. Introduction

The τ is the only lepton heavy enough to decay into hadrons. It produces light meson resonances with less background than any other mesonic decay or hadron production process (as in *e.g.*, $B\overline{B}$ decays). Measuring branching fractions for hadronic τ decay provides a method to confirm important Standard Model parameters: strong coupling constant (α_s) and $|V_{us}|$. [1] However, Cabbibo and/or phase space suppression has resulted in limited statistics for studies of kaon production in hadronic τ decay, even decades after the discovery of the τ. [2, 3] In this analysis we use a data sample of 669 fb^{-1} corresponding to $616{\times}10^6$ $\tau^+\tau^-$ pair events, which is two orders-of-magnitude larger than those that were available prior to the B-factory experiments.

The Belle experiment operated at the KEKB asymmetric-energy e$^+$ e$^-$ collider [4] running in the energy range of the $\Upsilon(4S)$, a copious source of $B\overline{B}$ pairs. In addition to $B\overline{B}$ pairs, $\tau^+\tau^-$ pairs are produced with a comparable cross section[6]. The $\tau^+\tau^-$ produced at the $\Upsilon(4S)$ are in a very clean experimental environment with low background.

The Belle detector [5] is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL), all located inside a superconducting solenoid coil that provides a 1.5 Tesla magnetic field. An iron flux-return located outside the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere

In order to optimize the event selection and estimate the signal efficiency and background, tau generic Monte Carlo(MC) samples generated using KORALB/TAUOLA [7]. The signal efficiency is taken carefully into account by applying the appropriate efficiency corrections for charged tracks and reconstructed neutral particles and by checking the hadron decay model dependencies. Backgrounds from τ and non-τ sources are estimated by tau-generic and $q\overline{q}$ generic MC samples.

Since the branching fractions for purely leptonic τ decays are measured with good precision, normalization to the number of τ leptonic decay events is used:

$$\mathcal{B}(\tau \to X) = \frac{N_{sig}}{\epsilon_{sig}} \frac{\epsilon_{e\text{-}\mu}}{N_{e\text{-}\mu}} \frac{\mathcal{B}(\tau \to e\bar{\nu}\nu)\mathcal{B}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{B}(\tau \to l\bar{\nu}\nu)}, (1)$$

where X is the signal decay mode under study, $\epsilon_{e\text{-}\mu}$ &

ϵ_{sig} are the efficiencies for detection and selection of e-μ events and signal events, respectively, and $N_{e\text{-}\mu}$ and N_{sig} are the number of selected e-μ pair and signal events, respectively. (For ϵ_{sig} determination the generated event ,N_{init}, have only τ forced to decay purely leptonically, which reduces some systematic errors, *e.g.*, the tracking efficiency, the particle identification efficiency, etc.

2. Event selection

The event selection starts by reconstructing four charged tracks and any number of photons, satisfying the requirement for the transverse momentum p_t > 0.1 GeV and energy of each photon E_γ > 0.1 GeV. Backgrounds from two-photon and Bhabha events are reduced by requiring the missing momentum, $p^2_{miss} = (p_{init} - \Sigma p_{track} - \Sigma p_\gamma)^2$, and its polar angle ($\theta_{miss}$) with respect to the beam direction in the center of mass(CM) to be in the ranges 1 GeV < p_{miss} < 7 GeV and 30° < θ_{miss} < 150°, respectively. Each tau event is divided into two hemispheres along the thrust-axis obtained using the momentum of all the tracks and photons in the CM frame, and each event is required to have three tracks on the one side of hemisphere (signal side) and only one track on the other side (tag side). Using particle identification(PID) likelihood variables ($\mathcal{L}$) based on the ratio of the energy deposited in the ECL to the momentum measured in the SVD and CDC, shower shape in the ECL, the particles range in the KLM, hit information from the ACC, dE/dx measured in the CDC, and the particles time of flight, a likelihood ratio defined as $\mathcal{P}(i/j) = \mathcal{L}_i/(\mathcal{L}_i + \mathcal{L}_j)$, where $\mathcal{L}_i(\mathcal{L}_j)$ is the likelihood of the observed detector response for a track with flavor i (j). This likelihood ratio is used to identify the electron/muon track on tag side by the requirements $\mathcal{P}(e) > 0.9$ / $\mathcal{P}(\mu) > 0.9$. The remaining single track on the signal side after K_S reconstruction using two tracks is identified as $\mathcal{P}(\pi|K) > 0.3$ for a pion and $\mathcal{P}(K|\pi) > 0.7$ for charged kaon.

$K_S \to \pi^+\pi^-$ is reconstructed by a vertex fit using the momentum of two oppositely charged tracks on the signal side. The additional conditions for K_S selection are the flight length (fl), 2 cm < fl < 20 cm, the closest distance of approach along the beam direction of the daughter tracks, z_{dist} < 2.5 cm, and the invariant mass of the two pions, 0.485 GeV/c^2 < $M_{\pi\pi}$ < 0.512 GeV/c^2. The $\pi^0 \to \gamma\gamma$ is reconstructed from the invariant mass determined from the momentum vectors of two photons detected on the signal side. The invariant mass-difference distribution of the two photons normalized by the resolution, $S_{\gamma\gamma} = \frac{m_{\gamma\gamma} - m_{\pi^0}}{\sigma_{\gamma\gamma}}$, is used to determine the number of genuine π^0s and to estimate the level of background using mass sidebands. The resolution of the invariant mass of the two photons varies from 4 to 9 MeV/c^2 according to the reconstructed momentum. The $S_{\gamma\gamma}$ signal region is defined as $-6 < S_{\gamma\gamma} < 5$.

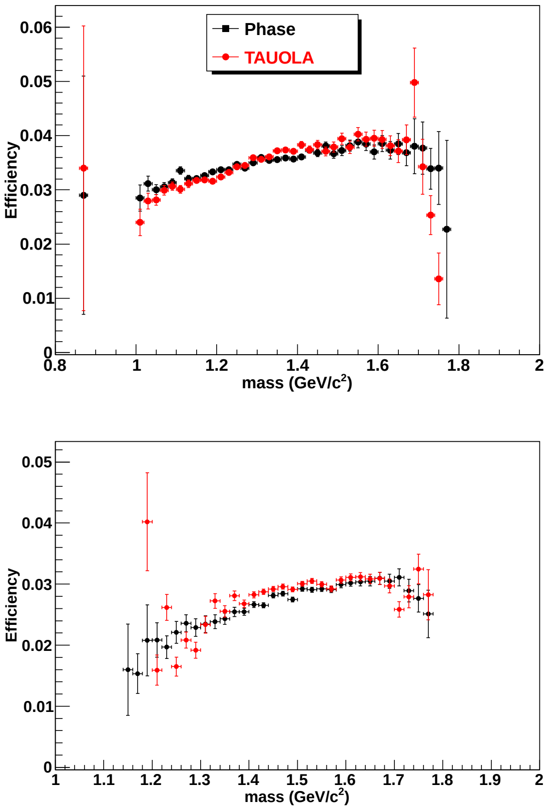

Figure 1: The difference in efficiency as a function of hadron mass between two hadron decay models for $\tau^- \to \pi^- K_S \pi^0 \nu_\tau$(up) and $\tau^- \to K^- K_S \pi^0 \nu_\tau$ (down). TAUOLA is the model implemented on KORALB/TAUOLA event generator with two resonances: $K_1(1270)$ and $K_1(1400)$ and Phase is the event generated uniformly over phase spaces

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In the final step, the highest energy of any remaining photon (E^{ex}_γ) is required to be E^{ex}_γ < 0.2 GeV in order to reduce the contribution from multiple π^0 decay modes. The total number of events satisfying the selection criteria for $\tau^- \to \pi^- K_S \pi^0 \nu_\tau$ ($\tau^- \to K^- K_S \pi^0 \nu_\tau$) is 35505 ± 188 (10652 ± 104) events from a total sample of 616 million τ pairs.

3. Efficiency

In order to determine the signal efficiency, a 17.2 million $\tau^+\tau^-$ MC sample is used. The difference, however, between MC and data is inevitable and corrections associated with differences between MC and data for particle identification and the reconstruction of the neutral particles, K_S and π^0 have to be evaluated. Correction tables for charged pions and kaons as a function of momentum and polar angle are generated from studies of large $D^* \to D^0\pi^-$ and $D^0 \to K^+\pi^-$ control samples; corrections for electron and muon tracks are derived from two-photon events.

The efficiency for K_S reconstruction as a function of momentum has been studied using a K_S control sample from the decay chain $D^* \to \pi_s D^0, D^0 \to K_S\pi^+\pi^-$. The average correction for the K_S reconstruction efficiency is (0.979 ± 0.041)% The π^0 efficiency correction is obtained by using the ratios of branching fraction for $\tau^- \to \pi^-\pi^0\nu_\tau$ channel which has been determined with $\delta\mathcal{B}/\mathcal{B} = 0.3\%$ accuracy and confirmed by several experiments.[8, 9]. Using $\tau^- \to \pi^-\pi^0\nu_\tau$ events in our data sample, the MC-data correction is determined to be (0.968 ± 0.015)%

The decay model implemented on the tau MC sample can contribute to the efficiency uncertainty. These contributions can be studied by weighting sets of MC samples generated with different hadron decay models. In this analysis, the efficiency difference as a function of hadronic mass has been checked using two MC samples, one that is generated using a hadron model containing two resonances: $K_1(1270)$ and $K_1(1400)$ (TAUOLA), and the other that is generated uniformly over phase space (Phase). By applying weighting factors obtained from the shape of data distribution to MC distributions, the difference in efficiency between the two decay models is found to be 0.26% (3.42%) for $\pi K_S\pi^0$ ($KK_S\pi^0$) mode (see Fig. 2). The differences are not too significant for the efficiency determination. To subtract the contribution from spurious π^0s, sideband of $S_{\gamma\gamma}$ is defined that has a different efficiency; more details are discussed in Sec.4.

After all corrections and subtractions, the final efficiency for the $\pi K_S\pi^0$ ($KK_S\pi^0$) mode is determined to be (2.68 ± 0.03)% ((2.19 ± 0.05) %).

4. Background

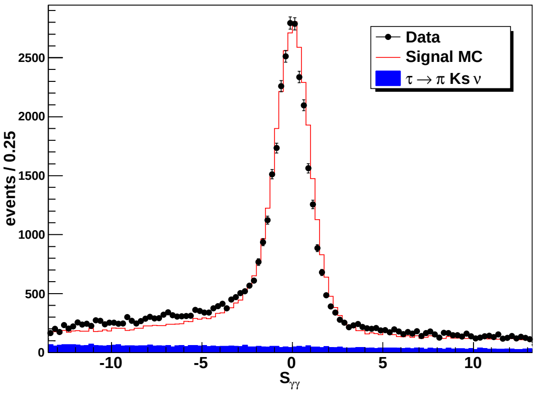

Figure 2: The normalized $M_{\gamma\gamma}$ distribution, $S_{\gamma\gamma}$ for the $\tau^- \to \pi^- K_S\pi^0\nu_\tau$ event sample. The non-π^0 background, $\tau \to \pi K_S\nu_\tau$, has a linear shape and is subtracted using the level of sideband events

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Since the branching fractions for τ decays to neutral kaon decays are not well studied, the determination of backgrounds from other τ decays have to be carefully considered. To determine the background, tau generic MC samples generated using branching ratios provided by the Particle Data Group(PDG) are used. However, some decay channels such as $\pi K_S K_S$ and $\pi K_S K_S\pi^0$, are expected to make large contributions to the background of $\pi K_S\pi^0$ mode but do not actually contribute as much as the MC expectation, because of overestimation of their branching fractions in former studies. In order to make a more precise background determination, we measured the branching fractions for $\tau \to \pi K_S K_S\nu$ and $\tau \to \pi K_S K_S\pi^0\nu$ using our data.

The subtraction of spurious π^0 uses the sideband region in $S_{\gamma\gamma}$ defined as $-13 < S_{\gamma\gamma} < -8$ and $7 < S_{\gamma\gamma} < 11$; spurious π^0s in the signal region are subtracted according to the formula :

$$N' = N^{SIG} - \frac{11}{9}N^{SB} \qquad (2)$$

Here N', N^{SIG} and N^{SB} stand for the number of subtracted, signal region and sideband region, respectively. Using this subtraction, the spurious π^0 backgrounds from $\tau^- \to \pi^- K_S\nu_\tau$ or $\tau^- \to K^- K_S\nu_\tau$ are reduced to less than 1% of total number of candidates. However the subtraction also reduces the total number of candidates and the efficiency for the $\pi K_S\pi^0$ ($KK_S\pi^0$) channels by 25% and 16% (22% and 17%), respectively

The background contributions to each decay mode are summarized in Table 4 The dominant backgrounds for $\pi^- K_S\pi^0$ mode are $\pi K_S K_S$ (3.58%) and $KK_S\pi^0$ (7.87%) and the total background contribution from τ decays is found to be 15.7%. The dominant background

Decay	$\pi^- K_S \pi^0$ (%)	$K^- K_S \pi^0$(%)
$K^- (\pi^-) K_S \pi^0$	7.87	12.7
$\pi^- K^0 \bar{K}^0$	3.58	0.35
$h^- K_S$	0.02	(0.07)
$\pi^- K_S \pi^0 \pi^0$	1.65	(-)
$\pi^- K^0 \bar{K}^0 \pi^0$	1.10	(-)
tag mis-ID	0.96	0.93
other τ decays	0.80	0.98
2-γ	0.12	0.25
$q\bar{q}$	0.78	0.41
total BG	16.9	15.6

Table 1: The background contents for $\tau^- \to \pi^- K_S \pi^0 \nu$ and $\tau^- \to K^- K_S \pi^0 \nu$. These two decay modes feed down to each other as background with dominant contribution. The spurious π^0 events are reduced by the subtraction($h^- K_S$). The parenthesis indicates the minus number ($h^- K_S$) due to the subtraction or the unobserved events($\pi^- K_S \pi^0 \pi^0$, $\pi^- K^0 \bar{K}^0 \pi^0$).

for $K^- K_S \pi^0$ mode are $\pi^- K_S \pi^0$ (12.7%) and the total background contribution from τ decays is found to be 14.9%.

The non-τ decay contributions are relatively small, at a level of 1%, and dominated by $q\bar{q}$ continuum events. For the estimation of contribution from $q\bar{q}$ continuum events, we consider events in the invariant mass distribution for each τ decay mode under study from a large $q\bar{q}$ MC sample that are in the hadronic mass region accessible in τ decays and normalizied by a factor α determined from events in the mass region above the kinematically allowed limit for τ decays. Explicitly, we minimize $S(\alpha) = \sum_i (h_i^{data} - (h_i^{non-qq} + \alpha \times h_i^{qq}))^2$, where i is a mass bin number and the sum is over masses above m_τ, h_i^{data} is the data distribution h_i^{non-qq} is the background distribution from non-$q\bar{q}$ sources and h_i^{qq} is the MC $q\bar{q}$ background distribution.

The total background in data for $\pi^- K_S \pi^0$ and $K^- K_S \pi^0$ are estimated to be 16.9% and 15.6% of total number of candidates, respectively.

5. Systematic uncertainties

The dominant systematic uncertainties comes from tracking and π^0 efficiencies. The uncertainty from charged track finding efficiency is 1.0 % per single charged track, however, the normalization using e-μ event reduces this uncertainty to a net number of two tracks: 2.1%. The uncertainty from π^0 efficiency is determined from the $\tau^- \to \pi^- \pi^0 \nu_\tau$ samples. The dominant uncertainty for the π^0 efficiency comes from the method for counting the number of signal π^0s and subtracting the spurious π^0 background. Two methods, one using the subtraction of sideband events and the other using fits with a logarithm Gaussian, are used to estimate the signal and background π^0. The uncertainty from π^0 efficiency is found to be 1.57% in total. The uncertainty due to PID has been studied for electrons and muons using two-photon events and for charged pion and kaons using $D^* \to D^0 \pi^-$ and $D^0 \to K^+ \pi^-$ samples. The uncertainty for electrons and muons are 2.5% for each, however, the e-μ normalization method reduces this uncertainty to 1.63%. The reconstruction of K_S can change the branching fractions. The uncertainty from K_S reconstruction is estimated by using a K_S control sample from the $D^* \to \pi_s D^0, D^0 \to K_S \pi^+ \pi^-$ decay chain. By varying the requirements on z_{dist}, the flight length and $M_{\pi\pi}$, the uncertainty from K_S reconstruction is determined to be 1.03% (1.37%) for $\pi K_S \pi^0$ ($K K_S \pi^0$). The background uncertainty is estimated by varying the fractions according to their uncertainties in the PDG tables to be 2.27% (1.54%) for $\pi K_S \pi^0$ ($K K_S \pi^0$). The shape of mass distribution for signal MC model used in this analysis is not perfectly matched to that of data, however the distortion is not too large. Errors introduced the hadron decay model can be caused by angular correlations between final-state particles. We find that different hadron decay models can cause the branching fraction shifts of 0.28% (3.42%) for $\pi K_S \pi^0$ ($K K_S \pi^0$). The e-μ normalization adds a relatively minor contribution to the uncertainty of 0.15%. The uncertainty from the energy restriction on extra photons in the signal hemisphere is estimated to be 0.60% (0.67%). When all these uncertainties are added in quadrature, the total systematic uncertainties for $\pi K_S \pi^0$ ($K K_S \pi^0$) are 4.65% (5.60%).

6. Result

The final selected number for $\pi K_S \pi^0$ ($K K_S \pi^0$) after the subtraction of spurious π^0 is found to be 26605 ± 211 (8258 ± 114) events. Based on the numbers presented in previous sections and the formula given in Eq.1, the branching fractions for $\tau^- \to \pi^- K_S \pi^0 \nu$ and $\tau^- \to K^- K_S \pi^0 \nu_\tau$ are found to be (0.192 ± 0.002 ± 0.008)% and (0.074 ± 0.001 ± 0.004)%, respectively. These results are consistent and more precise than the previous measurement. We also measured the branching fractions for $\tau^- \to \pi^- K_S K_S \nu_\tau$ and $\tau^- \to \pi^- K_S K_S \pi^0 \nu_\tau$ modes to estimate the background contribution for $\tau^- \to \pi^- K_S \pi^0 \nu_\tau$ and the results are $(2.35 \pm 0.04 \pm 0.13) \times 10^{-4}$ and $(2.10 \pm 0.24 \pm 0.22) \times 10^{-5}$, respectively. Especially, the branching fraction for $\tau^- \to \pi^- K_S K_S \pi^0 \nu_\tau$ is the first measurement and more details will be presented in the future study.

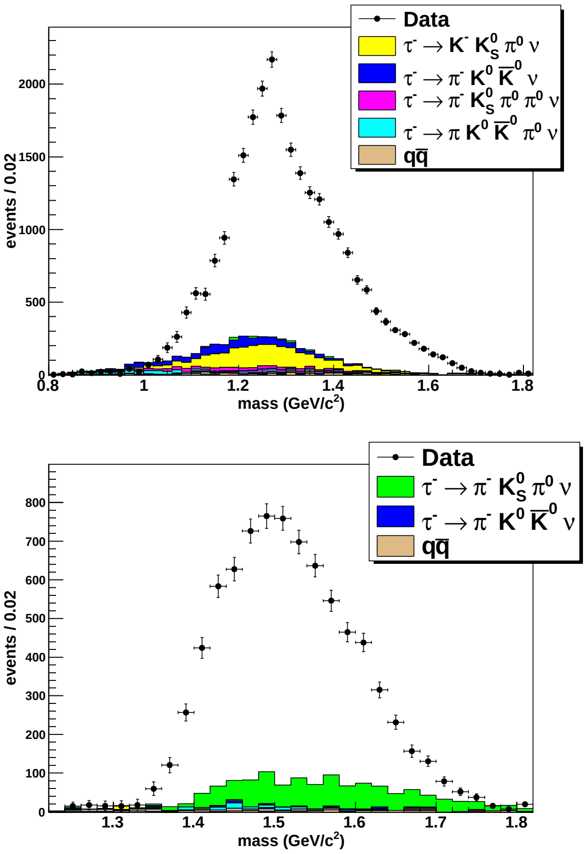

Figure 3: The invariant mass distribution for $\tau^- \to \pi^- K_S \pi^0 \nu_\tau$ (top) and $\tau^- \to K^- K_S \pi^0 \nu_\tau$ (bottom) with the estimated background (color shaded distribution) normalized by luminosity. The background distributions are cumulative.

7. Summary

Using a 669 fb^{-1} data sample containing 616 million τ pairs , we obtain branching fractions for the two semi-hadronic decay processes $\tau^- \to \pi^- K_S \pi^0 \nu_\tau$ and $\tau^- \to K^- K_S \pi^0 \nu_\tau$ with improved accuracy. The branching fraction are evaluated by normalizing to the $e\nu\bar{\nu}$ & $\mu\nu\bar{\nu}$ purely decay modes in order to reduce systematic uncertainties due to track-finding and PID uncertainties. The efficiency correction for PID and the reconstruction of neutral particles are determined by data driven methods. Different decay models, one based on TAUOLA and the other on phase space, are used to check the decay-model dependency of the efficiency determination. The appropriate background estimation by using MC and our measurement for the dominant background channels, $\tau^- \to \pi^- K_S K_S \nu_\tau$ and $\tau^- \to \pi^- K_S K_S \pi^0 \nu_\tau$ and the subtraction of spurious π^0 make possible to reduce the systematic uncertainties for the precise measurement. The results are: $\mathcal{B}(\tau^- \to \pi^- K_S \pi^0 \nu) = (0.192 \pm 0.002 \pm 0.008)\%$ and $\mathcal{B}(\tau^- \to K^- K_S \pi^0 \nu) = (0.074 \pm 0.001 \pm 0.004)\%$. These results are consistent with previous measurements, but with improved precision.

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