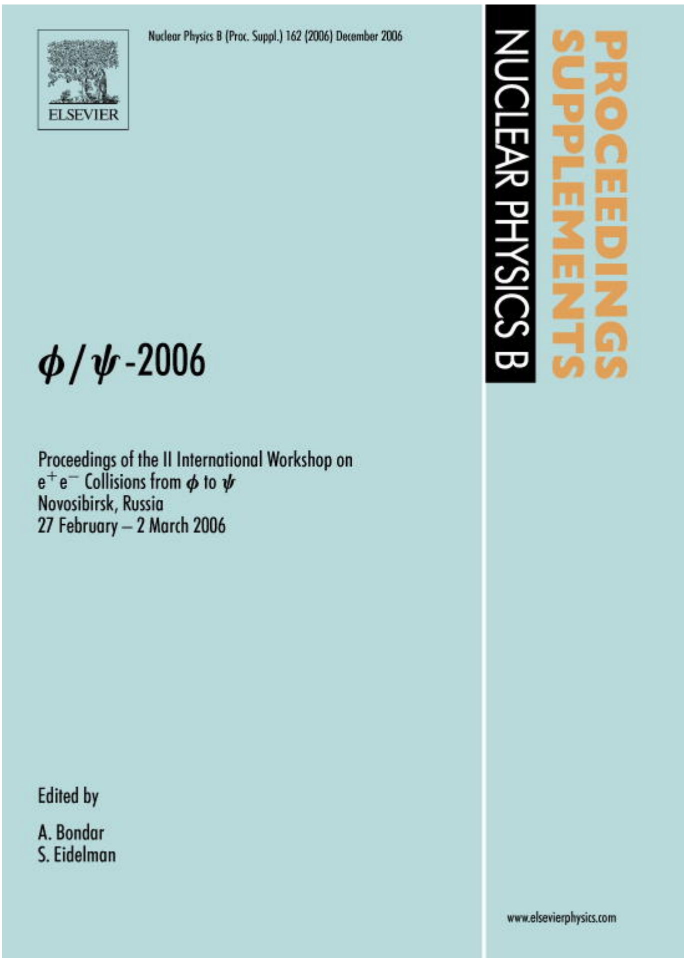
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Study of $\tau^- \to K_S\pi^-\nu_\tau$ decay with Belle

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We present a study of $\tau^- \to K_S\pi^-\nu_\tau$ decay using a data sample corresponding to the integrated luminosity of $\simeq 351 fb^{-1}$ collected by the Belle detector. Analysis is based on 55017 lepton tagged signal events. The measured branching ratio $Br(\tau \to K_S\pi\nu_\tau) = (0.391 \pm 0.004_{stat} \pm 0.014_{syst})\%$ is consistent with the PDG value and has much better accuracy. The invariant mass spectrum of $K_S\pi$ was analyzed. This spectrum is not saturated with the $K^\star(892)$ contribution only, so that other mechanisms are considered.

1. Introduction

τ lepton hadronic decays provide a good laboratory for a study of low energy hadronic currents under very clean conditions. In these decays a hadronic system is produced from the QCD vacuum due to the charged weak current mediated by a $W^\pm$ boson. In this case the τ decay amplitude can be factorized into a purely leptonic part including τ and ν_τ and a hadronic spectral function.

Being suppressed by a factor of 20 relative to the Cabibbo-allowed decay modes, strange τ decays induce special interest.

Low statistics of previous investigations [1],[2] makes difficult a detailed study of the strange hadronic spectral functions, which provide important information on the structure of the intermediate states. It was established that the main contribution to $K\pi$ spectra comes from the $K^*(892)$-meson [3]. However, possible scalar or tensor contributions are not excluded as well [4],[5].

The main goals of this work are a measurement of the $\tau^\pm \to K_S\pi^\pm\nu_\tau$ decay branching fraction with high precision as well as a study of the final state of this process.

2. Selection of $\tau^+\tau^-$ events

The Belle detector is a general purpose detector having excellent capabilities for precise vertex determination and particle identification. Tracking of charged particles is performed by a three-layer double-sided silicon vertex detector (SVD) and a fifty-layer cylindrical drift chamber (CDC) placed in the 1.5 T magnetic field. Charged hadrons are identified by means of dE/dx from the CDC, signal pulse-heights from aerogel Čerenkov counters (ACC), and timing information from time-of-flight scintillation counters (TOF). Energy of photons and electrons is measured using a CsI(Tl) electromagnetic calorimeter (ECL). Muons are detected by a fourteen-layer resistive plate counter interleaved with iron plates (KLM).

The present analysis is based on the events with one τ decaying to leptons while the other one goes to the hadronic channel. Events where both τ decay to leptons are used for normalization.

Selection of $\tau^+\tau^-$ events follows two stages to suppress background retaining high efficiency of decays under study.

1) The first stage criteria suppress beam background to the negligible level and reject main part of the background from the physical processes. These cuts retain a 46% efficiency for $\tau^+\tau^-$ events:

- Number of tracks, extrapolated to the interaction point within ± 0.5 cm transversely and ± 2.5 cm along the beam having transverse momentum in c.m.s. $|\vec{P}|_\perp^{CMS} > 0.1$ GeV/c: $2 \le N_{tracks} \le 4$
- Number of photons with energy in c.m.s. $E_\gamma^{CMS} > 80$ MeV: $N_\gamma \le 5$

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- Total charge of tracks $|Q_{total}| \leq 1$
- Sum of tracks absolute momenta in c.m.s. $P^{CMS} < 9$ GeV/c
- Total ECL energy deposition $\sum_{i=1}^{N_{clusters}} E_i^{LAB}(ECL) < 9$ GeV
- Maximum value of transversal momentum over tracks in laboratory system $|\vec{P}|_{\perp}^{LAB} > 0.5$ GeV/c
- Maximum opening angle over all pairs of tracks $\psi > 20^{o}$
- Total LAB energy of additional photons should be $\sum E_{\gamma}^{LAB} < 0.2$ GeV
- Missing mass 1 GeV/$c^2 \leq M_{mis} \leq 7$ GeV/c^2
- Polar angle of the missing momentum $30^{o} \leq \theta_{mis}^{CMS} \leq 150^{o}$

The last two criteria are especially effective against the background from radiative Bhabha, $\mu\mu$ and two-photon background processes.

2) After above criteria two event classes are selected for further processing:

- Two-lepton configuration sample $(l_1^{\pm}; l_2^{\mp}),\ l_1, l_2 = e; \mu$
- Lepton-hadron configuration sample $(l^{\pm}; K_S\pi^{\mp}),\ l = e, \mu$

Electrons are identified by means of an electron likelihood function ($\mathcal{L}_e$) which includes the information on the dE/dx measurement by CDC and the ratio of the cluster energy in the ECL to the track momentum measured in the CDC [12]. The muon likelihood function ($\mathcal{L}_\mu$) is evaluated from two variables - the difference between the range calculated from the momentum of a particle and the range measured by KLM as well as the χ^2 of the KLM hits with respect to the extrapolated track [13]. To select electrons $\mathcal{L}_e > 0.8$ cut is applied, for muons we require $\mathcal{L}_\mu > 0.8$.

To separate pions from kaons we determine the pion ($\mathcal{L}_\pi$) and kaon ($\mathcal{L}_K$) likelihoods from ACC response, the specific ionization (dE/dx) measurement in the CDC and the TOF flight-time measurement for each track, and form a likelihood ratio $\mathcal{L}_{K/\pi} = \mathcal{L}_K/(\mathcal{L}_\pi + \mathcal{L}_K)$ to separate pions and kaons. $\mathcal{L}_{K/\pi} < 0.3$ cut is applied to select pions.

To evaluate background and calculate efficiencies the $\tau^+\tau^-$ generic Monte Carlo sample of $N_{\tau\tau}^{MC} = 73.6 \times 10^6$ is produced with the KORALB/TAUOLA generator [9],[10] and the detector response is simulated by the GEANT3 [11].

2.1. Two-lepton events

To this class we select events with two leptons. Since (e, e) and (μ, μ) samples still contain about $\sim$ 50% contamination from events of radiation Bhabha and $\mu^+\mu^-(\gamma)$ processes, normalization was performed using (e, μ) events. For further $B\bar{B}$, $c\bar{c}$ background suppression we require:

$$cos(\vec{P_{l_1}}, \vec{P_{l_2}}) < 0,\ l_1 = e^{\pm}, l_2 = \mu^{\mp}$$

As a result, 2017905 events of $(e^+; \mu^-)$ type and 2028143 $(e^-; \mu^+)$ events were selected.

As it was found from MC simulation, the 6% contamination comes primarily from the events of the two-photon $e^+e^- \to e^+e^-\mu^+\mu^-$ process (2.5%) and from τ decays (3.4%).

2.2. Lepton-hadron events

To this class events with only one lepton $l^{\pm}(l = e,\ \mu)$, one K_S-candidate and one charged pion $\pi^{\mp}$ are selected.

K_S is reconstructed from its decay to the pair of oppositely charged pions having invariant mass within ± 14 MeV (5σ) of the K_S mass; the pion momenta are then recalculated with a K_S vertex constraint. The following criteria are imposed:

- Z-distance between the two helices at a $\pi^+\pi^-$ vertex position before the fit: $z_{dist} \leq 1.5$ cm
- The closest approach of at least one track to IP in the $R-\varphi$ plane is larger than 0.03 cm: $dr_1 \geq 0.03$ cm OR $dr_2 \geq 0.03$ cm
- The decay length of K_S-candidate in the $R-\varphi$ plane: $0.1 \leq l_{\perp}(K_S) \leq 20$ cm
- The Z-projection of the K_S-candidate decay length: $l_Z(K_S) \leq 20$ cm

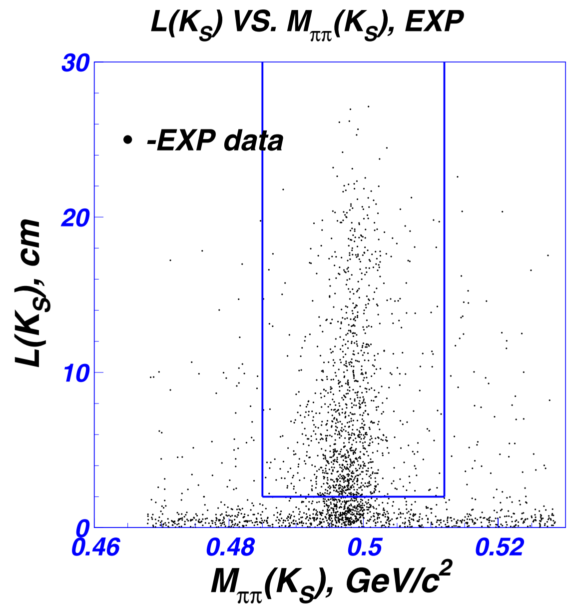

Figure 1. *K_S decay length VS. K_S invariant mass scatter plot of the experimental $(e^+; K_S\pi^-)$ events.*

- Cosine of the azimuthal angle between the momentum vector and the decay vertex vector of a K_S-candidate: $cos(d\phi) \geq 0.95$
- $cos(\vec{P_l}, \vec{P_h}) < 0,\ l = e^\pm, \mu^\pm;\ h = K_S, \pi^\pm$
- K_S decay length $L(K_S) > 2$ cm (see Fig.1)

68107 events were selected for further analysis. Figure 1 shows the selected events on the scatter plot: K_S decay length $L(K_S)$ versus $\pi^+\pi^-$ invariant mass of K_S-candidate $M_{\pi\pi}(K_S)$. Signal events are selected from the rectangular region; outside it are primarily the events of $\tau^\pm \to \pi^+\pi^-\pi^\pm\nu_\tau$ decay.

The main background comes from the τ decays with K_S: $\tau^\pm \to K_S\pi^\pm K_L\nu$, $\tau^\pm \to K_S\pi^\pm\pi^0\nu$, $\tau^\pm \to K_S K^\pm\nu$, $\tau^\pm \to \pi^\pm\pi^+\pi^-\nu$. Their contribution was calculated from luminosity, MC detection efficiencies and branching fractions [8], and it was found to be about 14%.

Events of $\tau \to 3\pi\nu$ decay contaminate the selected sample due to a fake K_S reconstructed from a pair of charged pions. The $M_{\pi\pi}(K_S)$ distribution of this fake K_S is flat in the region of the K_S mass, hence the number of 3π events is taken from the sideband regions on the $L(K_S)\ VS.\ M_{\pi\pi}(K_S)$ scatter plot, which have the same area as a signal one.

The fraction of signal events in the 3π-sideband region is about 1% and it was taken into account in the calculation of the MC signal detection efficiency. We observe a 5% fraction of 3π events in the signal region. The non-$\tau^+\tau^-$ background is found to be negligible.

3. $\tau \to K_S\pi\nu_\tau$ branching fraction

The $\tau \to K_S\pi\nu_\tau$ branching ratio is calculated according to the formula:

$$Br(K_S\pi^\mp\nu_\tau) = \frac{N(l_1^\pm; K_S\pi^\mp)}{N(l_1^\pm; l_2^\mp)} \cdot \frac{\varepsilon(l_1^\pm; l_2^\mp)}{\varepsilon(l_1^\pm; K_S\pi^\mp)} \times$$

$$\times Br(l^\mp\nu_l\nu_\tau),\ l_{1,2} = e, \mu, \quad (1)$$

where $N(l_1^\pm; K_S\pi^\mp)$, $\varepsilon(l_1^\pm; K_S\pi^\mp)$ are the number and MC efficiency of the signal $(l_1^\pm; K_S\pi^\mp)$ events, $N(l_1^\pm; l_2^\mp)$, $\varepsilon(l_1^\pm; l_2^\mp)$ are the number and MC efficiency of the two-lepton $(l_1^\pm; l_2^\mp)$ events, $Br(l^\mp\nu_l\nu_\tau)$ is the τ leptonic branching fraction, taken from [8].

It should be noticed that the tag lepton efficiency part is cancelled in the ratio of efficincies, so the related systematic uncertainty is reduced.

$\varepsilon(l_1^\pm; K_S\pi^\mp)$ and $\varepsilon(l_1^\pm; l_2^\mp)$ include the identification efficiencies which were determined using the events of two-photon processes $e^+e^- \to e^+e^-e^+e^-/\mu^+\mu^-$.

The dominant contribution to the branching fraction systematic uncertainty comes from K_S detection efficiency (2.5%), background subtraction (1.6%), lepton identification efficiency (1%) and pion identification efficiency(1%). The total systematic uncertainty of 3.5% was obtained by adding all the contributions in quadrature. As a result, we obtained:

$$Br(\tau \to K_S\pi\nu_\tau) = (0.391 \pm 0.004_{stat} \pm 0.014_{syst})\%$$

4. Analysis of $\tau \to K_S\pi\nu$ spectrum

The dynamics of $\tau \to K_S\pi\nu$ is studied by analysis of the $K_S\pi$ invariant mass distribution, which is approximated by the differential rate function:

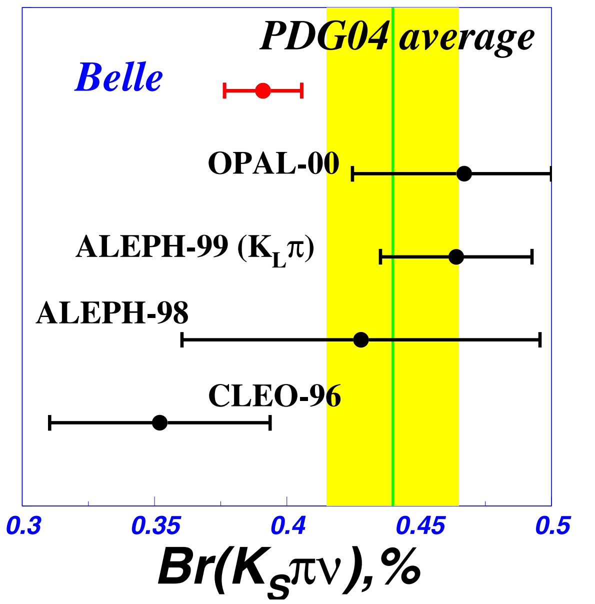

Figure 2. *Comparison of* $\tau^\pm \to K_S\pi^\pm\nu_\tau$ *branching fractions.*

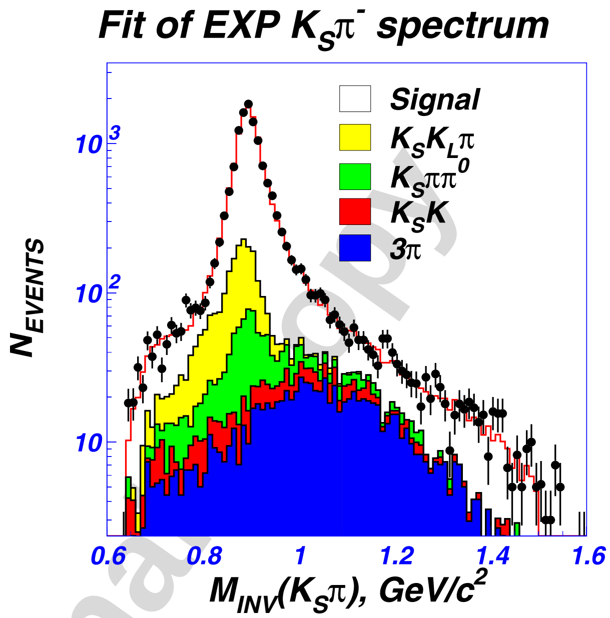

Figure 3. *Comparison of expected and experimental* $M_{INV}(K_S\pi)$ *distribution for the fit with* $K^\star(892)+\kappa+K^*(1410)$*, also shown are the contributions of background modes.*

$$\frac{d\Gamma}{d\sqrt{s}} \sim \frac{1}{s}\left(1-\frac{s}{m_\tau^2}\right)^2\left(1+2\frac{s}{m_\tau^2}\right)P\times$$

$$\times\left\{P^2|F_V|^2+\frac{3(m_K^2-m_\pi^2)^2}{4s(1+2\frac{s}{m_\tau^2})}|F_S|^2\right\}, \qquad (2)$$

where (see [4] for more detail) s is squared $K_S\pi$ invariant mass, P is K_S momentum in the $K_S\pi$ rest frame, the vector formfactor F_V is parametrized by $K^*(892)$ and $K^*(1410)$ meson amplitudes, the scalar formfactor F_S contains the scalar projections of $K^*(892)$, $K^*(1410)$ and additionally includes $K_0^*(800)(\kappa)$ and $K_0^*(1430)$ amplitudes. *LASS* parametrization of F_S is used.

The experimental distribution is approximated by the expected shape function, calculated as a convolution of the spectrum given by Eq.2 and apparatus function, taking into account efficiency nonuniformity and finite resolution.

It can be seen from the Table 1 that $K^\star(892)$ is not enough to describe $M_{INV}(K_S\pi)$ spectrum. To describe the enhancement of experimental events near threshold we introduce $K_0^\star(800)(\kappa)$ or use the LASS amplitude (see the third and second column of the Table 1), for description of the distribution at higher invariant masses we try to include the vector resonance $K^\star(1410)$ or scalar $K^\star(1430)$. Figure 3 demonstrates the best fit, its optimal parameters are shown in Table 1. As follows from this Table, even at the best fit the description is still quite poor. So, more sophisticated models are required.

Analyzing only $M_{INV}(K_S\pi)$ we can not resolve between $K_0^*(1430)$ and $K^*(1410)$, also the events enhancement near the invariant mass threshold is not clear understood.

The optimal value of $K^*(892)$ mass is 3-4 MeV higher than the world average [8]. Earlier all mass determinations came from hadronic reactions while our work presents the measurent based on τ decays.

5. Summary

The branching fraction of the $\tau^\pm \to K_S\pi^\pm\nu_\tau$ decay has been measured using a data

Table 1
$M_{INV}(K_S\pi)$ spectrum fit results, different models of non-$K^\star$ mechanism are tested: $K^*(1410)$ contribution is described by β complex constant, $K_0^*(1430)$ - γ, $K_0^*(800)(\kappa)$ - κ(real), LASS contribution is described by δ_{LASS}. The other parameters of K^* resonances were fixed at their PDG values.

	only-$K^\star(892)$	$K^\star(892) + A_{LASS} + K_0^*(1430)$	$K^\star(892) + \kappa + K^*(1410)$
$M_{K^\star(892)}$, MeV/c^2	895.6 ± 0.4	896.4 ± 0.4	896.4 ± 0.4
$\Gamma_{K^\star(892)}$, MeV	48.2 ± 1.1	47.2 ± 1.2	48.0 ± 1.1
$\lvert\beta\rvert$			0.039 ± 0.011
$arg(\beta)$			0.96 ± 0.55
$\lvert\gamma\rvert$		-2.8 ± 0.3	
$arg(\gamma)$		1.3 ± 0.3	
$\lvert\kappa\rvert$			0.53 ± 0.08
$\lvert\delta_{LASS}\rvert$		0.81 ± 0.07	
$arg(\delta_{LASS})$		-2.1 ± 0.2	
$a(LASS)$, (Gev/c)$^{-1}$		2.07-fixed	
$b(LASS)$, (Gev/c)$^{-1}$		3.32-fixed	
χ^2/ndf	282.8/76	176.0/72	122.5/72

sample of 351.4 fb^{-1} collected with the Belle detector. Our result is:

$$Br(\tau \to K_S\pi\nu_\tau) = (0.391 \pm 0.004_{stat} \pm 0.014_{syst})\%$$

It can be compared to the previous measurements of this branching fraction primarily by the *OPAL* [14], *ALEPH* [15] and *CLEO* [2] groups. In Fig.2 one can see the diagram with the world best measurements of the $\tau^\pm \to K_S\pi^\pm\nu_\tau$ branching fraction, its world average value [8] and our preliminary result.

Our result is in good agreement with the CLEO96 and ALEPH98 values and has a significantly smaller uncertainty, however, we observe $\sim 2\sigma$ difference between ALEPH99,OPAL00 values and our result.

Only $K^\star(892)$ is not enough to describe $K_S\pi$ the invariant mass spectrum. We tried to use several parametrizations, but still have not found proper description. A better model is needed.

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