Study of $\tau \to K\pi\nu$ decay at the B factories

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Recent results of high-statistics studies of the $\tau \to K\pi\nu$ decays at B factories are reviewed. We discuss precision measurements of the branching fractions of the $\tau^- \to K_S^0\pi^-\nu_\tau$ and $\tau^- \to K^-\pi^0\nu_\tau$ decays, and a study of the $K_S^0\pi^-$ invariant mass spectrum in the $\tau^- \to K_S^0\pi^-\nu_\tau$ decay. Searches for CP symmetry violation in the $\tau^- \to K_S^0\pi^-(\geq 0\pi^0)\nu_\tau$ decays are also briefly reviewed. We emphasize the necessity of the further studies of the $\tau \to K\pi\nu$ decays at B and Super Flavour factories.

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1 Introduction

The record statistics of τ leptons collected at the e^+e^- B factories [1] provide unique opportunities of the precision tests of the Standard Model (SM). In the SM, τ decays due to the charged weak interaction described by the exchange of W boson. Hence, there are two main classes of τ decays, leptonic and hadronic τ decays. Leptonic decays provide very clean laboratory to probe electroweak couplings [2], while hadronic τ decays offer unique tools for the precision study of low energy QCD [3]. The hadronic system is produced from the QCD vacuum via decay of the W^{-1} boson into $\bar{u}$ and d quarks (Cabibbo-allowed decays) or $\bar{u}$ and s quarks (Cabibbo-suppressed decays). As a result the decay amplitude can be factorized into a purely leptonic part including the τ^- and ν_τ and a hadronic spectral function.

Of particular interest are strangeness changing Cabibbo-suppressed hadronic τ decays. The decays $\tau^- \to \bar{K}^0\pi^-\nu_\tau$ and $\tau^- \to K^-\pi^0\nu_\tau$ (or, shortly, $\tau \to K\pi\nu$) provide the dominant contribution to the inclusive strange hadronic spectral function, which is used to evaluate s-quark mass and V_{us} element of Cabibbo-Kobayashi-Maskawa (CKM) quark flavor-mixing matrix [4]. In the $\tau \to K\pi\nu$ decays the $K\pi$ system is produced in the clean experimental conditions without disturbance from the final state interactions. Hence, $\tau \to K\pi\nu$ decays provide complementary information about K-π interaction to the experiments with kaon beams [5, 6]. In the leptonic sector, CP

[1]Unless specified otherwise, charge conjugate decays are implied throughout the paper.

symmetry violation (CPV) is strongly suppressed in the SM ($A_{SM}^{CP} \lesssim 10^{-12}$) leaving enough room to search for the effects of New Physics [7]. Of particular interest are strangeness changing Cabibbo-suppressed hadronic τ decays, in which large CPV could appear from a charged scalar boson exchange in some Multi-Higgs-Doublet models (MHDM) [8].

Recently, Belle and *BABAR* performed an extended study of the $\tau \to K\pi\nu$ decays and searches for CPV in these decays [9, 10, 11, 12, 13, 14].

2 Study of $\tau \to K\pi\nu$ decays at Belle and *BABAR*

The first analysis of $\tau^- \to K_S^0\pi^-\nu_\tau$ decay at Belle was done with a 351 fb^{-1} data sample that contains 323×10^6 $\tau^+\tau^-$ pairs [9]. So called lepton-tagged events were selected, in which τ^+ decays to leptons, $\tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau$, $\ell = e, \mu$, while the other one decays to the signal $K_S^0\pi^-\nu_\tau$ final state. Events where both τ's decay to leptons were used for the normalization. In the calculation of the $\tau^- \to K_S^0\pi^-\nu_\tau$ branching fraction the detection efficiencies for the signal and two-lepton events were determined from Monte Carlo (MC) simulation with the corrections from the experimental data. The obtained branching fraction:

$$\mathcal{B}(\tau^- \to K_S^0\pi^-\nu_\tau) = (4.04 \pm 0.02(\text{stat.}) \pm 0.13(\text{syst.})) \times 10^{-3}$$

is consistent with the other measurements. The $K_S^0\pi^-$ invariant mass distribution

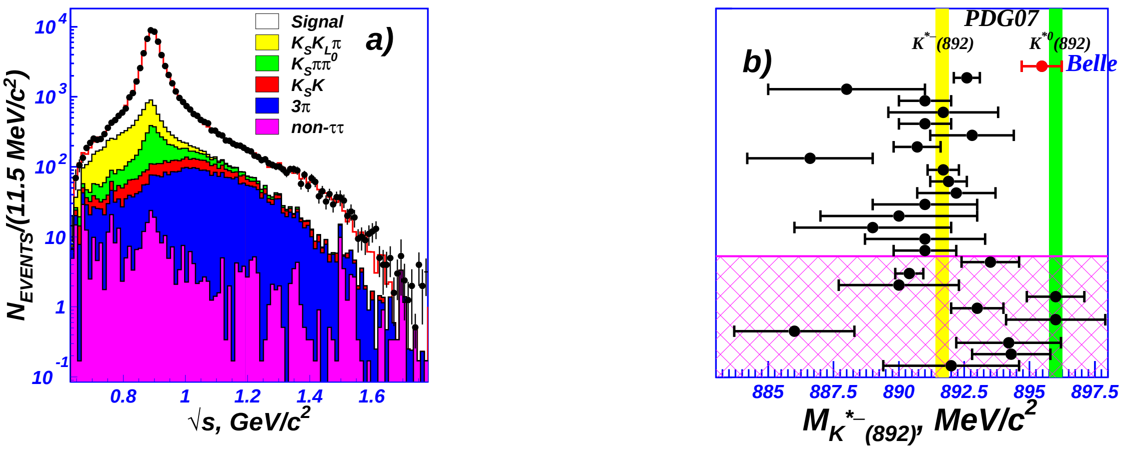


Figure 1: (a) The $K_S^0\pi$ mass distribution, points are experimental data, the histogram is the $K_0^*(800)^- + K^*(892)^- + K^*(1410)^-$ model; (b) The $K^*(892)^-$ mass measured in different experiments.

shown in Fig. 1 (a) is described in terms of the vector (F_V) and the scalar (F_S) form factors according to Ref. [16]:

$$\frac{d\Gamma}{d\sqrt{s}} \sim \frac{1}{s}\left(1-\frac{s}{m_\tau^2}\right)^2\left(1+2\frac{s}{m_\tau^2}\right)P\left\{P^2|F_V|^2+\frac{3(m_K^2-m_\pi^2)^2}{4s(1+2\frac{s}{m_\tau^2})}|F_S|^2\right\}, \quad (1)$$

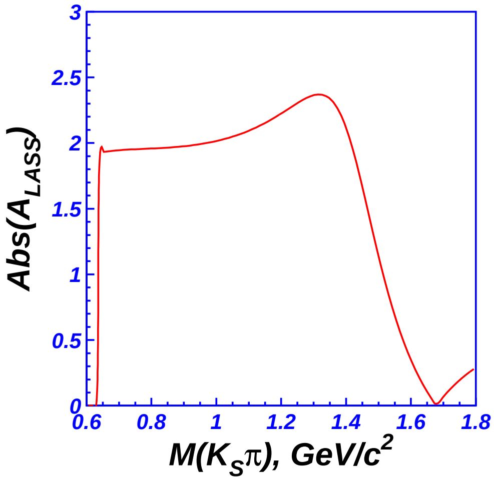
where s is squared $K_S^0\pi^-$ invariant mass, P is K_S^0 momentum in the $K_S^0\pi^-$ rest frame. The vector form factor is parametrized by the $K^*(892)^-$, $K^*(1410)^-$ and $K^*(1680)^-$ meson amplitudes, while the scalar form factor includes the $K_0^*(800)^-$ and $K_0^*(1430)^-$ contributions. The $K^*(892)^-$ alone is not sufficient to describe the $K_S^0\pi^-$ invariant mass spectrum. To describe the enhancement near threshold, we introduce a $K_0^*(800)^-$ amplitude, while for the description of the distribution at higher invariant masses we try to include the $K^*(1410)^-$, $K^*(1680)^-$ vector resonances or the scalar $K_0^*(1430)^-$. The best description is achieved with the $K_0^*(800)^- + K^*(892)^- + K^*(1410)^-$ and $K_0^*(800)^- + K^*(892)^- + K_0^*(1430)^-$ models. The parameterization of F_S suggested by the LASS experiment [5] was also tested:

$$F_S = \lambda\frac{\sqrt{s}}{P}(\sin\delta_B e^{i\delta_B} + e^{2i\delta_B}BW_{K_0^*(1430)}(s)), \quad (2)$$

where λ is a real constant, P is K_S^0 momentum in the $K_S^0\pi^-$ rest frame, and the phase δ_B is determined from the equation $\cot\delta_B = \frac{1}{aP} + \frac{bP}{2}$, where a, b are the model (fit) parameters. In this parameterization the non-resonant mechanism is given by the effective range term $\sin\delta_B e^{i\delta_B}$, while the resonant structure is described by the $K_0^*(1430)$ amplitude. The shape of the optimal scalar form factor in the LASS experiment strongly differs (especially, near the threshold of the $K_S^0\pi^-$ production) from that obtained in the fit of the $K_S^0\pi^-$ mass distribution in the study of $\tau^- \to K_S^0\pi^-\nu_\tau$ decay at Belle, see Fig. 2. There is large systematic uncertainty in the near $K_S^0\pi^-$ production threshold part of the spectrum due to the large background from the $\tau^- \to K_S^0\pi^-K_L^0\nu_\tau$ decay, whose dynamics is not precisely known. In the new study at B factories it will be possible to suppress this background essentially applying special kinematical constraints.

A fit to the $K_S^0\pi^-$ invariant mass spectrum also provides a high precision measurement of the $K^*(892)^-$ mass and width: $M(K^*(892)^-) = (895.47 \pm 0.20(\text{stat.}) \pm 0.44(\text{syst.}) \pm 0.59(\text{mod.}))$ MeV/c^2, $\Gamma(K^*(892)^-) = (46.2 \pm 0.6(\text{stat.}) \pm 1.0(\text{syst.}) \pm 0.7(\text{mod.}))$ MeV. While our determination of the width is compatible with most of the previous measurements within experimental errors, our mass value, see Fig. 1 (b), is considerably higher than those before and is consistent with the world average value of the neutral $K^*(892)^0$ mass, which is (896.00 ± 0.25) MeV/c^2 [15].

The second analysis of the $\tau^- \to K_S^0\pi^-\nu_\tau$ decay at Belle was based on the data sample with the luminosity integral of $\mathcal{L} = 669$ fb^{-1} which comprises 615 million $\tau^+\tau^-$ events [11]. One inclusive decay mode $\tau^- \to K_S^0X^-\nu_\tau$ and 6 exclusive hadronic τ decay modes with K_S^0 ($\tau^- \to K_S^0\pi^-\nu_\tau$, $\tau^- \to K_S^0K^-\nu_\tau$, $\tau^- \to K_S^0K_S^0\pi^-\nu_\tau$, $\tau^- \to$



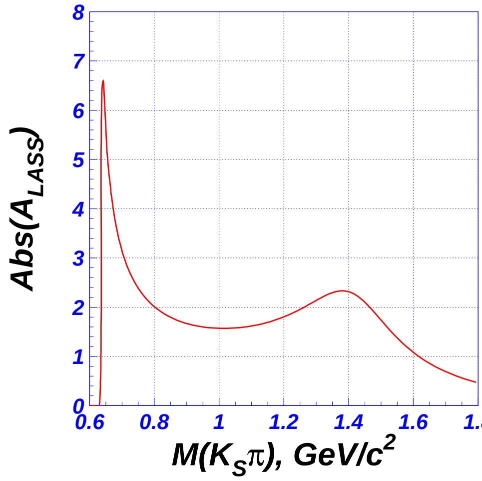


Figure 2: The absolute value of F_S from LASS experiment (left) and from the $\tau^- \to K_S^0\pi^-\nu_\tau$ study at Belle (right).

$K_S^0\pi^-\pi^0\nu_\tau$, $\tau^- \to K_S^0K^-\pi^0\nu_\tau$, $\tau^- \to K_S^0K_S^0\pi^-\pi^0\nu_\tau$) were studied in Ref. [11]. In this study signal events were tagged by one-prong tau decays (into $e\nu\nu$, $\mu\nu\nu$ or $\pi/K(n \geq 0)\pi^0\nu$ final states) with the branching fraction $\mathcal{B}_{1-\text{prong}} = (85.35 \pm 0.07)\%$. In total, 157836 events of the $\tau^- \to K_S^0\pi^-\nu_\tau$ decay were selected with the fraction of the non-cross-feed background of $(8.86 \pm 0.05)\%$ and the detection efficiency $\varepsilon_{\text{det}} = (7.09 \pm 0.12)\%$. The obtained branching fraction:

$$\mathcal{B}(\tau^- \to K_S^0\pi^-\nu_\tau) = (4.16 \pm 0.01(\text{stat.}) \pm 0.08(\text{syst.}))) \times 10^{-3}$$

supersedes the previous Belle result and has the best accuracy.

Precision measurement of the branching fraction of the $\tau^- \to K^-\pi^0\nu_\tau$ decay with a 230.2 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance has been carried out by *BABAR* [12]. The result:

$$\mathcal{B}(\tau^- \to K^-\pi^0\nu_\tau) = (4.16 \pm 0.03(\text{stat.}) \pm 0.18(\text{syst.}))) \times 10^{-3}$$

is consistent with the previous measurements and $\mathcal{B}(\tau^- \to K_S^0\pi^-\nu_\tau)$ and has the best accuracy. The $K^-\pi^0$ invariant mass distribution is shown in Fig. 3.

The preliminary result on the $\mathcal{B}(\tau^- \to K_S^0\pi^-\nu_\tau)$ using a 384.6 fb^{-1} data sample was also published by *BABAR* [13]:

$$\mathcal{B}(\tau^- \to K_S^0\pi^-\nu_\tau) = (4.20 \pm 0.02(\text{stat.}) \pm 0.12(\text{syst.}))) \times 10^{-3}.$$

It is consistent with the other measurements. The distribution of the invariant mass of the $K_S^0\pi^-$ system is shown in Fig. 3, experimental data exhibit additional contribution

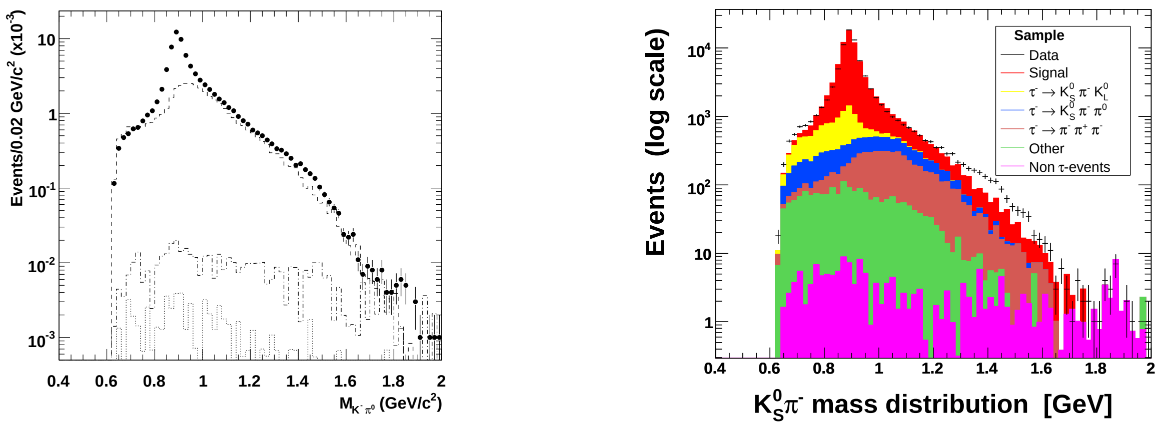


Figure 3: The $K^-\pi^0$ invariant mass distribution (left) from Ref. [12]. The dots are experimental data, histograms are background MC events with selection and efficiency corrections: background from $\tau\tau$ (dashed line), $q\bar{q}$ (dash-dotted line), $\mu^+\mu^-$ (dotted line). The $K^0_S\pi^-$ invariant mass distribution (right) from Ref. [13]. The dots are experimental data, histograms are signal and background MC: signal events (red), dominant background from the $\tau^- \to K^0_S K^0_L \pi^- \nu_\tau$ decay (yellow), non-$\tau\tau$ events (magenta).

around the invariant mass of 1.4 GeV/c^2, which is not included in the signal MC simulation.

3 Search for CPV in $\tau \to K\pi\nu$

Recent studies of CPV in the $\tau^- \to \pi^- K_S(\geq 0\pi^0)\nu_\tau$ decays at *BABAR* [14] as well as in the $\tau^- \to K_S\pi^-\nu_\tau$ decay at Belle [10] provide complementary information about sources of CPV in these hadronic decays.

The decay-rate asymmetry $A_{\rm CP} = \frac{\Gamma(\tau^+\to\pi^+K_S(\geq 0\pi^0)\nu_\tau)-\Gamma(\tau^-\to\pi^-K_S(\geq 0\pi^0)\nu_\tau)}{\Gamma(\tau^+\to\pi^+K_S(\geq 0\pi^0)\nu_\tau)+\Gamma(\tau^-\to\pi^-K_S(\geq 0\pi^0)\nu_\tau)}$ was studied at *BABAR* with the $\tau^+\tau^-$ data sample of $\int Ldt = 476$ fb^{-1}. The obtained result $A_{\rm CP} = (-0.36 \pm 0.23 \pm 0.11)\%$ is about 2.8 standard deviations from the SM expectation $A^{K^0}_{\rm CP} = (+0.36 \pm 0.01)\%$.

At Belle, CPV search was performed as a blinded analysis based on a 699 fb^{-1} data sample. Specially constructed asymmetry, which is a difference between the mean values of the $\cos\beta\cos\psi$ for τ^- and τ^+ events, was measured in bins of $K^0_S\pi^-$

mass squared ($Q^2 = M^2(K_S^0\pi)$):

$$A_i^{CP}(Q_i^2) = \frac{\int\limits_{\Delta Q_i^2} \cos\beta\cos\psi\left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right)d\omega}{\frac{1}{2}\int\limits_{\Delta Q_i^2}\left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}\right)d\omega} \simeq \langle\cos\beta\cos\psi\rangle_{\tau^-} - \langle\cos\beta\cos\psi\rangle_{\tau^+},$$

where β, θ and ψ are the angles, evaluated from the measured parameters of the final hadrons, $d\omega = dQ^2 d\cos\theta d\cos\beta$. In contrary to the decay-rate asymmetry the introduced $A_i^{CP}(Q_i^2)$ is already sensitive to the CPV effects from the charged scalar boson exchange [17]. No CP violation was observed and the upper limit on the CPV parameter η_S was extracted to be: $|\mathrm{Im}(\eta_S)| < 0.026$ at 90% CL. Using this limit parameters of the Multi-Higgs-Doublet models [18, 19] can be constrained as $|\mathrm{Im}(XZ^*)| < 0.15\ M_{H^\pm}^2/(1\,\mathrm{GeV}^2/c^4)$, where $M_{H^\pm}$ is the mass of the lightest charged Higgs boson, the complex constants Z and X describe the coupling of the Higgs boson to leptons and quarks respectively.

4 Further studies of $\tau \to K\pi\nu$ decays

In the analysis of the $\tau^- \to K_S^0\pi^-\nu_\tau$ decay, it is very desirable to measure separately vector (F_V), scalar (F_S) form factors and their interference. The $K^*(892)^-$ mass and width are measured in the vector form factor taking into account the effect of the interference of the $K^*(892)^-$ amplitude with the contributions from the radial exitations, $K^*(1410)^-$ and $K^*(1680)^-$. The scalar form factor is important to unveil the problem of the $K_0^*(800)^-$ state as well as for the tests of the various fenomenological models and search for CPV. The interference between vector and scalar form factors is necessary in the search for CPV in $\tau^- \to K_S^0\pi^-\nu_\tau$ decay.

To elucidate the nature of the $K^*(892)^- - K^*(892)^0$ mass difference it is important to study the following modes: $\tau^- \to K_S^0\pi^-\nu_\tau$, $\tau^- \to K_S^0\pi^-\pi^0\nu_\tau$, $\tau^- \to K_S^0K^-\pi^0\nu_\tau$. $K^*(892)^-$ mass and width can be measured in the clean experimental conditions without disturbance from the final state interactions in the $\tau^- \to K_S^0\pi^-\nu_\tau$ decay. While a study of the $\tau^- \to K_S^0\pi^-\pi^0\nu_\tau$ mode allows one to measure simultaneously in one mode the $K^*(892)^-(K_S^0\pi^-)$ and the $K^*(892)^0(K_S^0\pi^0)$ masses. The effect of the pure hadronic interaction of the $K^*(892)^-(K^*(892)^0)$ and $\pi^0(\pi^-)$ on the $K^*(892)^-(K^*(892)^0)$ mass can be precisely measured as well. It is also important to investigate precisely the effect of the pure hadronic interaction of the $K^*(892)^-(K^*(892)^0)$ and $K_S^0(K^-)$ on the $K^*(892)^-(K^*(892)^0)$ mass in the $\tau^- \to K_S^0K^-\pi^0\nu_\tau$ decay.

5 Summary

Belle and $BABAR$ essentially improved the accuracy of the branching fractions of the $\tau^- \to (K\pi)^-\nu_\tau$ decays. At Belle the $K_S^0\pi$ invariant mass spectrum was studied and the $K^*(892)^-$ alone is not sufficient to describe the $K_S^0\pi$ mass spectrum. The best description is achieved with the $K_0^*(800)^- + K^*(892)^- + K^*(1410)^-$ and $K_0^*(800)^- + K^*(892)^- + K_0^*(1430)^-$ models. For the first time the the $K^*(892)^-$ mass and width have been measured in τ decay at B factories. The $K^*(892)^-$ mass is significantly different from the current world average value, it agrees with the $K^*(892)^0$ mass. Precision study of the $\tau^- \to K_S^0\pi^-\nu_\tau$, $\tau^- \to K_S^0\pi^-\pi^0\nu_\tau$ and $\tau^- \to K_S^0K^-\pi^0\nu_\tau$ decays at the B factories as well as the $e^+e^- \to K_S^0K^\pm\pi^\mp$ reaction at the VEPP-2000 [20, 21] and $K-\pi$ scattering amplitude at the coming GlueX experiment [6] could provide additional valuable information about the $K^*(892)^-$ mass, namely unveil an impact of the hadronic and electromagnetic interactions in the final state.

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