Search for CP violation in $\tau^- \rightarrow K_S \pi^- \nu_\tau$ decays at Belle

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1. Introduction

- CP violation is so far observed only in the B and K systems.
- No CP violation has been observed in the lepton sector.
- Finding CPV in lepton sector is a clean signal of the New Physics.
- For this purpose, tau lepton provides an unique opportunity, since tau is an only lepton that can decay to hadrons, which provides strong phases that are needed to make the CPV as observable in the decay processes.
- In tau decays, one can search for CPV effects of possible new physics that could originate from (generic) MSSM as well as multi-Higgs-Doublet-Models (MHDM).

1.1 CP violation in $\tau^- \rightarrow K_s \pi^- \nu_\tau$ decays

- Two source of CP asymmetries in $\tau^- \rightarrow K_s \pi^- \nu_\tau$
  - CP rate asymmetry from known physics of CPV in $K^0 - \bar{K}^0$ (Bigi, Sanda 2005)
    \[
    \frac{\Gamma(\tau^+ \rightarrow K_s \pi^+ \nu_\tau) - \Gamma(\tau^- \rightarrow K_s \pi^- \nu_\tau)}{\Gamma(\tau^+ \rightarrow K_s \pi^+ \nu_\tau) + \Gamma(\tau^- \rightarrow K_s \pi^- \nu_\tau)} = 3.3 \times 10^{-3}
    \]
  - CP Asymmetry in the angular distribution (Kuhn, Mirkes 1993).
    - Generally possible if there are interference between the SM diagram and the CP violating scalar boson exchange diagrams.
    - Effective Hamiltonian

    \[H_{NP} = \sin \theta_c \frac{G}{\sqrt{2}} \left( \overline{\nu} (1 + \gamma_5) \tau \right) \left( \overline{s} \gamma_\mu (1 - \gamma_5) u \right) \]

Current Analysis focuses on the CPV in the angular distribution.
1.2 Generic Scalar Form Factor

- In \( \tau^- \rightarrow K_s \pi^- \nu_\tau \), there are two form factors, vector \( (F(Q^2)) \) and scalar \( F_s(Q^2) \).

\[
J^K_\mu = \langle K(p_1)\pi(p_2) | \bar{s} \gamma_\mu u | 0 \rangle \\
= (p_1 - p_2)^\mu T_{\nu\mu} F(Q^2) + Q_\mu F_s(Q^2)
\]

\[
T_{\mu\nu} = g_{\mu\nu} - \frac{Q_\mu Q_\nu}{Q^2}
\]

- Effect of CP violating scalar boson exchange diagram can be introduced generally by replacing the SM scalar form factor as follows (Kuhn, Mirkes)

\[
F_s(Q^2) \rightarrow F_s(Q^2) = F_s(Q^2) + \frac{\eta_s}{m_\tau} F_H(Q^2)
\]

\[
F_H(Q^2) = \langle K(p_1)\pi(p_2) | \bar{s} u | 0 \rangle
\]

where \( \eta_s \) is the dimensionless complex coupling constant. That changes as \( \eta_s \rightarrow \eta_s^* \) for the CP conjugate processes, \( \tau^- \rightarrow \tau^+ \).
1.3 Differential decay width

Differential Decay Width for \( \tau^- \rightarrow K_S \pi^- \nu_\tau \)

\[
\frac{d\Gamma(\tau^-)}{dQ^2 d \cos \theta d \cos \beta} = \left[ A(Q^2) - B(Q^2)(3 \cos^2 \Psi - 1)(3 \cos^2 \beta - 1) \right] \cdot |F|^2 + m_\tau^2 |F_s|^2 \\
- C(Q^2) \cos \beta \cos \Psi \cdot \text{Re}(F F_s^*(\eta_s))
\]

- \( Q^2 = M_{K\pi}^2 \), \( A(Q^2), B(Q^2), C(Q^2) \): known function.
- \( \beta \): direction of \( K_S \) in \( K_S \pi \) rest frame
- \( \Psi \): direction of \( t \) in the \( K_S \pi \) rest frame.
- \( (\theta \text{ direction of } K_S \pi \text{ system in the } t \text{ rest frame. Correlated with } \Psi) \)

- Note:
  - Interference term contains the CPV effect and is proportional to \( \cos \beta \cos \Psi \)
  - The sign of the int. term is reversed for \( \tau^- \) and \( \tau^+ \)
  - Integrated decay-rate is the same for \( \tau^- \) and \( \tau^+ \)
2. Analysis Method

- In order to extract CP violating term proportional to \( \cos \beta \cos \Psi \), following observable \( A_{cp} \) is defined for each bin of \( Q^2 = (M_{K\pi})^2 \)

\[
A_{cp}^w(Q^2) = \frac{\int \left( \frac{d\Gamma_{\tau^-}}{d\omega} \cdot \cos \beta \cos \Psi - \frac{d\Gamma_{\tau^+}}{d\omega} \cdot \cos \beta \cos \Psi \right) d\omega}{\int \left( \frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega} \right) d\omega}
\]

where \( d\omega = dQ^2 d\cos \beta d\cos \Psi \)

✓ In other word, \( A_{cp}^w \) is the difference between the mean values of \( \cos \beta \cos \Psi \) for \( \tau^- \) and \( \tau^+ \) in bins of \( Q^2 \)

\[
A_{cp}^w \equiv \langle \cos \beta \cos \Psi \rangle_{\tau^-} - \langle \cos \beta \cos \Psi \rangle_{\tau^+}
\]
3. Data

- **Data**: based on Upsilon(4S) + off-resonance 699 fb⁻¹

- **Selection criteria for** $\tau^- \rightarrow K_s \pi^- \nu_\tau$
  
  - Divide two-hemispheres in CMS, Thrust>0.9,
  
  - Signal side; $L_{ID}(\pi/K)>0.7$, $K_s$: decay length > 2cm, $0.485\text{GeV}<M_{\pi\pi}<0.511\text{GeV}$, No additional $\gamma$ ($E_\gamma>0.2\text{GeV}$)
  
  - Tag side: 1 prong (e, $\mu$ or $\pi (n \geq 0)\pi^0$)
3.1 $M(K_s\pi)$ distribution, rate-asymmetry

- $\tau^+ \rightarrow K_s\pi^+\nu_\tau$ : $(162,168 \pm 403)$ events
- $\tau^- \rightarrow K_s\pi^-\nu_\tau$ : $(161,982 \pm 403)$ events

**Background**: total $(22.1 \pm 3.6)$%
- $\tau \rightarrow K_s K_L \pi \nu_\tau$: $(9.5 \pm 3.2)$%
- $\tau \rightarrow K_s \pi \pi^0 \nu_\tau$: $(3.7 \pm 1.2)$%
- $e^+e^- \rightarrow qq$: $(3.4 \pm 1.0)$%

**CP rate-asymmetry (Observed level)**

$$A_{CP} = \frac{N(\tau^+ \rightarrow K_s\pi^+\nu_\tau) - N(\tau^- \rightarrow K_s\pi^-\nu_\tau)}{N(\tau^+ \rightarrow K_s\pi^+\nu_\tau) + N(\tau^- \rightarrow K_s\pi^-\nu_\tau)} = (0.07 \pm 0.25)\%$$

- Consistent with zero asymmetry.
- Consistent with SM prediction of $+0.33\%$ within one sigma.
- c.f. Similar sensitivity to the recent Babar result, arxiv:1109.1527
4. Corrections and Checks

- Analysis is carried out by blinding the signal in the “Ks” signal region.
- Check on the potential source of artificial CPV using $\tau^{-}\rightarrow\pi^{-}\pi^{+}\pi^{-}\nu_{\tau}$ events
  - FB ($\gamma$-Z int.) asymmetry
    (measure as a function of $\theta_{3\pi}$ in lab. system)
  - Asymmetries induced by detector
    (measure as a function of $p$ and $\theta$ of particle in lab. system.)
- These corrections are applied in event-by-event basis.

The net effect of corrections to $A_{\text{w}}^{\text{cp}}$ is small since the $A_{\text{w}}^{\text{cp}}$ is measured as a function of angle relative to $\tau$ direction not in Lab. angles.

$\gamma$-Z: $0(10^{-4})$
Detector: $0(10^{-3})$
4.1 Check of no biasness by MC and Data

- **Check of algorithm by MC**
  - "Expected" CP asymmetry using typical parameterization of FF.
    - red: when $\text{Im}(\eta_s)=0.1$
    - (Note: current limit $|\text{Im}(\eta_s)|<0.19$ CLEO2002)

- **Check for bias using data.**
  - Measure $A_{cp}$ using the events of $K_s$ side band region in $\tau^-\rightarrow\pi^-\pi^+\pi^-\nu_\tau$
    - $456\text{MeV}<M_{\pi\pi}<482\text{MeV}$, $514\text{MeV}<M_{\pi\pi}<540\text{MeV}$
    - Black: w/o any correction
    - Blue: with corrections of FB and detector introduced charge asymmetry.

No CPV is observed

Ready for opening the Blind
5. Results

\[ A_{cp} = (1.8 \pm 2.1(stat) \pm 1.4(sys)) \times 10^{-3} \text{ for } 0.89 \leq M_{K\pi} \leq 1.11 GeV \]

Black: Results in Ks signal region.
Blue: Acp in Ks sideband region.
Red: Acp when \( \eta_S = 0.1 \)

\( \tau^\pm \to \nu_\tau K_S^0 \pi^\pm \)
5-1. Extraction of limit for $\text{Im} \eta_s$

**Relation between $A_{cp}$ and $\text{Im}(\eta_s)$**

\[
A_{cp}' = \text{Im}(\eta_s) \frac{N_s}{n_i} \int_{Q_{i,j}} C(Q^2) \frac{\text{Im}(FF^*_H)}{m_\tau} dQ^2, \quad C(Q^2); \text{known function}\]

- Use our previous results of Form Factor $F$ and $F_s$ obtained a fit to the $K_s\pi$ mass spectrum.
- Float the relative const. phase $\phi_s$ btw $F$ and $F_s$, which cannot be determined only from mass spectrum.

Form Factors (2)

![Form Factors Graph](image)

\[C(Q^2)\]
# 5-2. Results and Application

## Results

\[ |\text{Im}(\eta_s)| < (0.012-0.026) \text{ at 90 } \%\text{C.L.} \]

- The limit depend on the parameterization of the Form Factor.
- One order of magnitude more restrictive than the previous CLEO results \(|\text{Im}(\eta_s)| < 0.19\)

## Application: In the 3HDM

\[ \eta_s \equiv \frac{m_\tau}{M_{H^+}^2} m_s \ X^* \ Z \]

- \(M_{H^+}\) : mass of lightest charged Higgs in MHDM
- \(Z\) : complex coupling constant btw Higgs and lepton.
- \(X\) : complex coupling constant btw Higgs and down-type quark

### The result \((\text{Im}(\eta_s) < 0.026)\) limits the couplings:

\[ |\text{Im}(XZ^*)| \leq 0.15 \frac{M_H^2}{(1\text{GeV})^2} \]

phi-psi 2011
Belle has searched for the CP violation in $\tau^- \rightarrow K_s \pi^- \nu_\tau$ decay using 699fb$^{-1}$ data. The analysis based on the angle weighted asymmetry $A_{\text{cp}}^w$ shows no evidence for CP violation at $O(10^{-3})$ level.

$$A_{\text{cp}}^w = (1.8 \pm 2.1 \text{(stat)} \pm 1.4 \text{(sys)}) \times 10^{-3} \text{ for } 0.89 \leq M_{K\pi} \leq 1.11 \text{GeV}$$

Using the measured spectrum of $K_s \pi$ system, we obtain the limit for the imaginary part of CPV parameter $\eta_s$ ,

$$|\text{Im}(\eta_s)| < (0.012 - 0.026) \text{ at 90 \%C.L.}$$

This is one order of magnitude more stringent than the previous CLEO’s results.

This result limits the product of the coupling constants $(X,Z)$ in the multi-Higgs doublet model to be

$$|\text{Im}(XZ^*)| \leq 0.15 \frac{M_H^2}{(1\text{GeV})^2}$$

See arxiv:1101.0349v1 for more details. Accepted by PRL.
Backup