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

D. Epifanov (BINP, NSU)

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**Outline:**

1. **Introduction**
2. **Study of $\tau^- \to K_S^0\pi^-\nu_\tau$, $K^-\pi^0\nu_\tau$**
3. **CPV in $\tau^- \to K_S^0\pi^-(\geq 0\pi^0)\nu_\tau$**
4. **Further studies at $B$ factories**
5. **Summary**

π-K Interactions Workshop

February 14-15, 2018
Jefferson Lab • Newport News, VA

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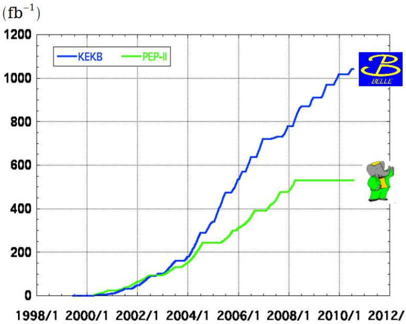
# Introduction

- The world largest statistics of $\tau$ leptons collected by $e^+e^-$ $B$ factories (Belle and *BABAR*) opens new era in the precision tests of the Standard Model (SM).
- In the SM $\tau$ decays due to the charged weak interaction described by the exchange of $W^\pm$ with a pure vector coupling to only left-handed fermions. There are two main classes of $\tau$ decays:
  - Decays with leptons, like: $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$, $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau \gamma$, $\tau^- \to \ell^- \ell'^+ \ell'^- \bar{\nu}_\ell \nu_\tau$; $\ell, \ell' = e, \mu$. They provide very clean laboratory to probe electroweak couplings, which is complementary/competitive to precision studies with muon (in experiments with muon beam). Plenty of New Physics models can be tested/constrained in the precision studies of the dynamics of decays with leptons.
  - **Hadronic decays of $\tau$ offer unique tools for the precision study of low energy QCD.**

# Introduction: $e^+e^-$ $B$ factories

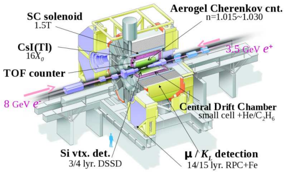
**Integrated luminosity of B factories**



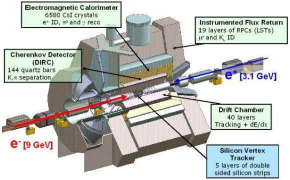
**$> 1$ ab$^{-1}$**
**On resonance:**
$\Upsilon(5S)$: 121 fb$^{-1}$
$\Upsilon(4S)$: 711 fb$^{-1}$
$\Upsilon(3S)$: 3 fb$^{-1}$
$\Upsilon(2S)$: 25 fb$^{-1}$
$\Upsilon(1S)$: 6 fb$^{-1}$
**Off reson./scan:**
$\sim 100$ fb$^{-1}$

**$\sim 550$ fb$^{-1}$**
**On resonance:**
$\Upsilon(4S)$: 433 fb$^{-1}$
$\Upsilon(3S)$: 30 fb$^{-1}$
$\Upsilon(2S)$: 14 fb$^{-1}$
**Off resonance:**
$\sim 54$ fb$^{-1}$

Belle Detector



BABAR detector



$$\sigma(b\bar{b}) = 1.05\ \text{nb}\ N_{b\bar{b}} = 1.2 \times 10^9$$
$$\sigma(c\bar{c}) = 1.30\ \text{nb}\ N_{c\bar{c}} = 2.0 \times 10^9$$
$$\sigma(\tau\tau) = 0.92\ \text{nb}\ N_{\tau\tau} = 1.4 \times 10^9$$

**B-factories are also charm- and $\tau$-factories !**

# Introduction: hadronic $\tau$ decays

Cabibbo-allowed decays ($\mathcal{B} \sim \cos^2\theta_c$)

$\mathcal{B}(S=0) = (61.85 \pm 0.11)\%$ (PDG)

Cabibbo-suppressed decays ($\mathcal{B} \sim \sin^2\theta_c$)

$\mathcal{B}(S=-1) = (2.88 \pm 0.05)\%$ (PDG)

$$iM_{\rm fi}\left\{\begin{array}{c} S=0 \\ S=-1 \end{array}\right\} = \frac{G_{\rm F}}{\sqrt{2}}\overline{u}_{\nu_\tau}\gamma^\mu(1-\gamma^5)u_\tau \cdot \left\{\begin{array}{l} \cos\theta_{\rm c}\cdot\langle\text{hadrons}(q^\mu)|\hat{J}_\mu^{S=0}(q^2)|0\rangle \\ \sin\theta_{\rm c}\cdot\langle\text{hadrons}(q^\mu)|\hat{J}_\mu^{S=-1}(q^2)|0\rangle \end{array}\right\},\ q^2 \le M_\tau^2$$

## The main tasks

- Measurement of branching fractions with highest possible accuracy
- Measurement of low-energy hadronic spectral functions
  - Determination of the decay mechanism (what are intermediate mesons and their contributions)
  - Precise measurement of masses and widths of the intermediate mesons
- Search for CP violation
- Comparison with hadronic formfactors from $e^+e^-$ experiments to check CVC theorem
- Measurement of $\Gamma_{\rm inclusive}(S=0)$ to determine $\alpha_S$
- Measurement of $\Gamma_{\rm inclusive}(S=-1)$ to determine s-quark mass and $V_{\rm us}$:

$$|V_{\rm us}| = \sqrt{\frac{R_{\rm strange}}{\frac{R_{\rm non-strange}}{|V_{\rm ud}|^2} - \delta R_{\rm theory}}}$$

- $R_{\rm strange} = \mathcal{B}_{\rm strange}/\mathcal{B}_{\rm e}$
- $R_{\rm non-strange} = \mathcal{B}_{\rm non-strange}/\mathcal{B}_{\rm e}$
- $\delta R_{\rm theory}$ - SU(3)-breaking contribution

# Study of the $\tau^- \to K_S^0\pi^-\nu_\tau$ decay

- **Measurement of $\mathcal{B}(\tau \to K_S^0\pi\nu_\tau)$ branching ratio:** $\tau \to \bar{K}^0\pi\nu_\tau$ has the largest $\mathcal{B}$ among decays with one kaon, so, it provides the dominant contribution to the s-quark mass sensitive total strange hadronic spectral function.
- **Study of the $K_S^0\pi$ dynamics (mass spectrum):**
  M. Finkemeier, E. Mirkes, Z. Phys. C **72**, 619 (1996).
  The hadronic current in the case of two pseudoscalar hadrons with $q^\mu_{1,2}$:

  $$J^\mu = F_V(q^2)\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)(q_1 - q_2)_\nu + F_S(q^2)q^\mu,\ q^\mu = q_1^\mu + q_2^\mu$$

  - $F_V$: $K^*(892)^\pm$, $K^*(1410)^\pm$, $K^*(1680)^\pm$;
  - $F_S$: $K^*(800)^\pm(\kappa)$, $K^*(1430)^\pm$;
  - Precision measurement of $M(K^*(892)^\pm)$ and $\Gamma(K^*(892)^\pm)$.
- **CPV in $\tau \to K_S^0\pi\nu_\tau$**
  - J.Kuhn, E.Mirkes,Phys. Lett. **B398**, 407 (1997).
  - Y. Grossman and Y. Nir, JHEP **1204**, 002 (2012).
  - J. P. Lees *et al.* [BABAR], Phys. Rev. D **85**, 031102 (2012).
  - M. Bischofberger *et al.* [Belle], Phys. Rev. Lett. **107**, 131801 (2011).

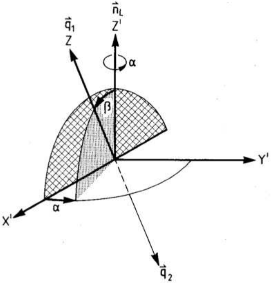
# $\tau \to K\pi\nu_\tau$ hadronic spectral functions

$$d\Gamma = \frac{G_F^2}{256\pi^3 m_\tau}\sin^2\theta_c\{L_{\mu\nu}H^{\mu\nu}\}\left(1-\frac{q^2}{m_\tau^2}\right)|\vec{q}_1|\frac{dq^2}{\sqrt{q^2}}\frac{d\alpha}{2\pi}\frac{d\cos\beta}{2}\frac{d\cos\theta}{2}$$

$$L_{\mu\nu}H^{\mu\nu} = 2m_\tau^2\left(1-\frac{q^2}{m_\tau^2}\right)(\overline{L}_B W_B + \overline{L}_{SA} W_{SA} + \overline{L}_{SF} W_{SF})$$

$$W_B = 4|\vec{q}_1|^2|F_V|^2,\ W_{SA} = q^2|F_S|^2,\ W_{SF} = 4\sqrt{q^2}|\vec{q}_1|\mathrm{Re}[F_V F_S^*]$$

$$\overline{L}_B = \frac{1}{3}\left(2+\frac{m_\tau^2}{q^2}\right)-\frac{1}{6}\left(1-\frac{m_\tau^2}{q^2}\right)(3\cos^2\psi-1)(3\cos^2\beta-1),\ \overline{L}_{SA} = \frac{m_\tau^2}{q^2},\ \overline{L}_{SF} = -\frac{m_\tau^2}{q^2}\cos\psi\cos\beta$$



$$\cos\beta = -\vec{n}_q \cdot \frac{\vec{q}_1}{|\vec{q}_1|}$$

$$\cos\theta = \frac{(2\frac{E_{K\pi}}{E_\tau}-1-\frac{q^2}{m_\tau^2})}{(1-\frac{q^2}{m_\tau^2})\sqrt{1-m_\tau^2/E_\tau^2}}$$

$$\cos\psi = \frac{\frac{E_{K\pi}}{E_\tau}(m_\tau^2+q^2)-2q^2}{(m_\tau^2-q^2)\sqrt{(E_{K\pi}^2-q^2)/E_\tau^2}}$$

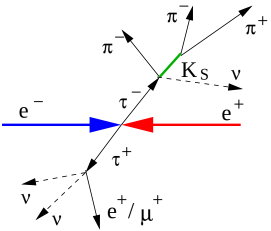
# Measurement of $\mathcal{B}(\tau^- \to K_S^0 \pi^- \nu_\tau)$

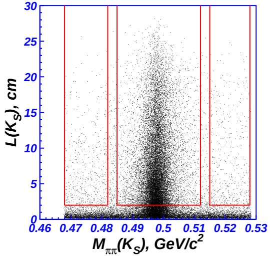
D. EPIFANOV *et al.* [BELLE], PHYS. LETT. B **654**, 65 (2007).

Statistics: $\int Ldt = 351\ \text{fb}^{-1}$, $N_{\tau\tau} = 323 \times 10^6$

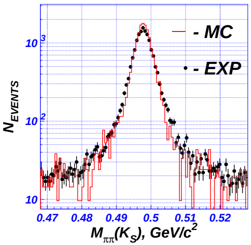
53110 signal events with efficiency $\varepsilon_{\text{det}} \simeq 6\%$.

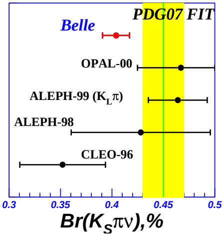
Two-lepton ($\tau \to e\nu\nu, \tau \to \mu\nu\nu$) events are used for normalization.



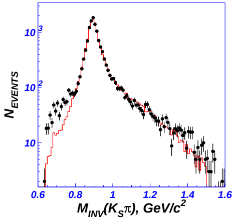


**Distribution over $M_{\pi\pi}(K_S)$**





**Fit with K*(892) only**



| Mode | Contents, % |
|---|---|
| $K_S\pi\nu$ | 79 |
| $K_S\pi K_L\nu$ | 9 |
| $K_S\pi\pi^0\nu$ | 4 |
| $K_S K\nu$ | 2 |
| $3\pi\nu$ | 5 |
| non-$\tau\tau$ | 1 |

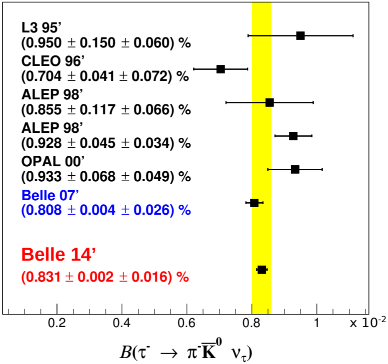
$$\boldsymbol{\mathcal{B}(\tau^- \to K_S\pi^-\nu_\tau) = (0.404 \pm 0.002(\text{stat.}) \pm 0.013(\text{syst.}))\%}$$

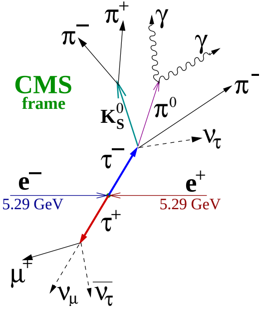
# Study of $\tau^- \to K_S^0 X^- \nu_\tau$ decays at Belle

S. Ryu *et al.* [Belle], Phys. Rev. D **89**, 072009 (2014)

Data sample of $\int L dt = 669$ fb$^{-1}$ with $N_{\tau\tau} = 616 \times 10^6$ was used to study inclusive decay $\tau^- \to K_S^0 X^- \nu_\tau$ as well as 6 exclusive modes:

$$\begin{array}{ccc} \pi^- K_S^0 \nu_\tau & K^- K_S^0 \nu_\tau & \pi^- K_S^0 K_S^0 \nu_\tau \\ \pi^- K_S^0 \pi^0 \nu_\tau & K^- K_S^0 \pi^0 \nu_\tau & \pi^- K_S^0 K_S^0 \pi^0 \nu_\tau \end{array}$$



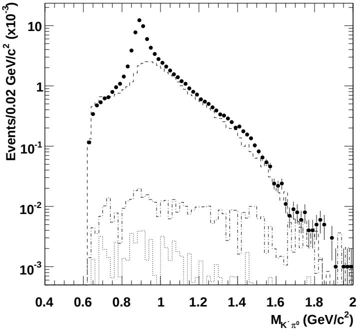


$$\mathcal{B}(\tau^- \to K_S^0 \pi^- \nu_\tau) = (4.16 \pm 0.01 \pm 0.08) \times 10^{-3}$$
$$\mathcal{B}(\tau^- \to K_S^0 X^- \nu_\tau) = (9.14 \pm 0.01 \pm 0.22) \times 10^{-3}$$

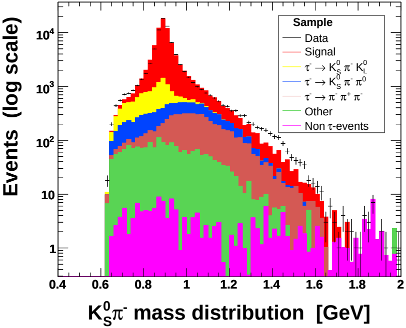
# Study of $\tau \to K\pi\nu$ at *BABAR*

B. Aubert *et al.* [BaBar], Phys. Rev. D **76**, 051104 (2007).
B. Aubert *et al.* [BaBar], Nucl. Phys. Proc. Suppl. **189**, 193 (2009).

$\tau^- \to K^-\pi^0\nu_\tau$



$\tau^- \to K^0_S\pi^-\nu_\tau$



$$\mathcal{B}(\tau^- \to K^-\pi^0\nu_\tau) = (0.416 \pm 0.003(\mathrm{stat.}) \pm 0.018(\mathrm{syst.}))\%$$
$$\mathcal{B}(\tau^- \to K^0_S\pi^-\nu_\tau) = (0.420 \pm 0.002(\mathrm{stat.}) \pm 0.012(\mathrm{syst.}))\%\ (\mathrm{preliminary})$$

# Study of the $K_S^0\pi$ mass spectrum at Belle

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

$$\mathrm{F_V} = \frac{\mathrm{BW_{K^*(892)}} + \mathrm{a(K^*(1410))} \cdot \mathrm{BW_{K^*(1410)}} + \mathrm{a(K^*(1680))} \cdot \mathrm{BW_{K^*(1680)}}}{1 + \mathrm{a(K^*(1410))} + \mathrm{a(K^*(1680))}}$$

$$\mathrm{F_S} = \mathrm{a(K_0^*(800))} \cdot \mathrm{BW_{K_0^*(800)}} + \mathrm{a(K_0^*(1430))} \cdot \mathrm{BW_{K_0^*(1430)}}$$

$$\mathrm{BW_X} = \frac{\mathrm{M_X^2}}{\mathrm{M_X^2 - s - i\sqrt{s}\text{`}_X(s)}}$$

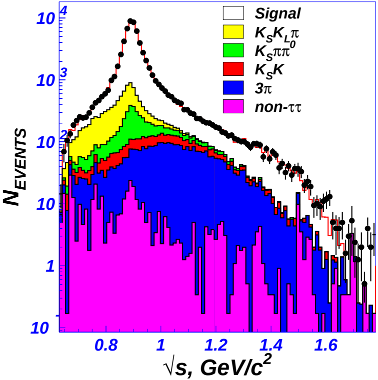
$$\Gamma_X(s) = \Gamma_X\frac{\mathrm{M_X^2}}{\mathrm{s}}\left(\frac{\mathrm{P(s)}}{\mathrm{P(M_X^2)}}\right)^{2\ell+1} \cdot \mathrm{F_R^{\ell 2}}$$

$$\mathrm{P(s)} = \frac{\sqrt{\mathrm{(s-(M_K+M_\pi)^2)(s-(M_K-M_\pi)^2)}}}{2\sqrt{\mathrm{s}}}$$

| Spin $\ell$ | Blatt-Weisskopf factor $\mathrm{F_R^\ell}$ |
|---|---|
| 0 | 1 |
| 1 | $\sqrt{\frac{1+R^2P^2(M_X^2)}{1+R^2P^2(s)}}$ |
| 2 | $\sqrt{\frac{9+3R^2P^2(M_X^2)+R^4P^4(M_X^2)}{9+3R^2P^2(s)+R^4P^4(s)}}$ |

# $K_0^*(800) + K^*(892) + K^*(1410)$

The $K^*(892)$ alone is not sufficient to describe the $K_S^0\pi$ spectrum



$$M_{K^*(892)} = 895.47 \pm 0.20\ \mathrm{MeV/c^2}$$

$$\Gamma_{K^*(892)} = 46.19 \pm 0.57\ \mathrm{MeV}$$

$$|\mathrm{a(K^*(1410))}| = (75 \pm 6) \times 10^{-3}$$

$$\arg(\mathrm{a(K^*(1410))}) = 1.44 \pm 0.15$$

$$|\mathrm{a(K_0^*(800))}| = 1.57 \pm 0.23$$

$$\chi^2/\mathrm{Ndf} = 90.2/84,\ P(\chi^2) = 30\%$$

We take $K_0^*(800)$ parameters:
$M_{K_0^*(800)} = (878 \pm 23 \pm 60)\ \mathrm{MeV/c^2}$, $\Gamma_{K_0^*(800)} = (499 \pm 52 \pm 71)\ \mathrm{MeV/c^2}$ from:
M. ABLIKIM *et al.*, [BES COLLABORATION], PHYS. LETT. B **633**, 681 (2006).

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.

# $K_0^*(800) + K^*(892) + K_0^*(1430)$

| | solution 1 | solution 2 |
|---|---|---|
| $M_{K^*(892)}$, MeV/c$^2$ | $895.42 \pm 0.19$ | $895.50 \pm 0.22$ |
| $\Gamma_{K^*(892)}$, MeV | $46.14 \pm 0.55$ | $46.20 \pm 0.69$ |
| $\|a(K_0^*(1430))\|$ | $0.954 \pm 0.081$ | $1.92 \pm 0.20$ |
| $arg(a(K_0^*(1430)))$ | $0.62 \pm 0.34$ | $4.03 \pm 0.09$ |
| $a(K_0^*(800))$ | $1.27 \pm 0.22$ | $2.28 \pm 0.47$ |
| $\chi^2/ndf$ | $86.5/84$ | $95.1/84$ |
| $P(\chi^2), \%$ | 41 | 19 |
| $\mathcal{B}(K_0^*(1430) \to K_S\pi)$ | $1/3$ | $1/3$ |
| $\mathcal{B}(\tau \to K_0^*(1430)\nu_\tau)$ | $(13 \pm {}^{3}_{2}) \times 10^{-5}$ | $(54 \pm {}^{18}_{9}) \times 10^{-5}$ |

M. Z. YANG, "TESTING THE STRUCTURE OF THE SCALAR MESON $K_0^*(1430)$ IN $\tau \to K_0^*(1430)\nu_\tau$ DECAY", MOD. PHYS. LETT. A **21**, 1625 (2006) [ARXIV:HEP-PH/0509102]:

$$\mathcal{B}(\tau \to K_0^*(1430)\nu_\tau) = (7.9 \pm 3.1) \times 10^{-5}$$

# LASS parametrization of $F_S$

P. Estabrooks, Phys. Rev. D **19**, 2678 (1979).
D. Aston *et al.* (LASS), Nucl. Phys. B **296**, 493 (1988).

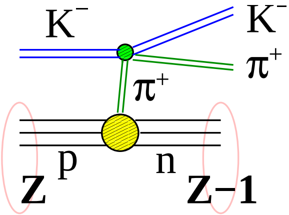
$$F_S = \lambda \frac{M_{K\pi}}{P}(\sin\delta_{\rm B} e^{i\delta_{\rm B}} + e^{2i\delta_{\rm B}} BW_{K_0^*(1430)}(M_{K\pi}))$$

$$\cot\delta_{\rm B} = \frac{1}{aP} + \frac{bP}{2}$$

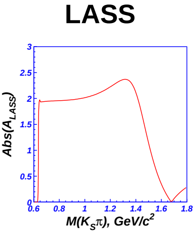
$$a = (2.07 \pm 0.10)\ ({\rm GeV/c})^{-1}$$

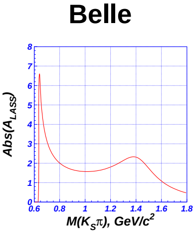
$$b = (3.32 \pm 0.34)\ ({\rm GeV/c})^{-1}$$

$$P = \frac{\sqrt{(M_{K\pi}^2-(M_{\rm K}+M_\pi)^2)(M_{K\pi}^2-(M_{\rm K}-M_\pi)^2)}}{2M_{K\pi}}$$



| | $K^*(892)$+LASS<br>$a, b$-fixed | $K^*(892)$+LASS<br>$a, b$-free |
|---|---|---|
| $M_{K^*}$, ${\rm MeV/c^2}$ | $895.42 \pm 0.19$ | $895.38 \pm 0.23$ |
| $\Gamma_{K^*}$, MeV | $46.46 \pm 0.47$ | $46.53 \pm 0.50$ |
| $\lambda$ | $0.282 \pm 0.011$ | $0.298 \pm 0.012$ |
| $a$, $({\rm GeV/c})^{-1}$ | $2.13 \pm 0.10$ | $10.9 + 7.4 - 3.0$ |
| $b$, $({\rm GeV/c})^{-1}$ | $3.96 \pm 0.31$ | $19.0 + 4.5 - 3.6$ |
| $\chi^2$/n.d.f. | $196.9/86$ | $97.3/83$ |
| $P(\chi^2)$, % | $10^{-8}$ | 13 |





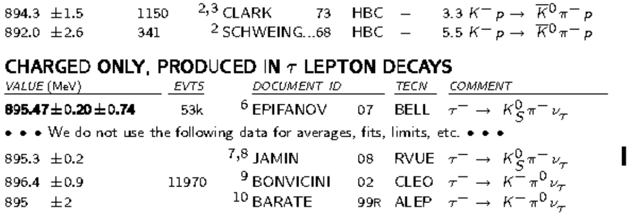
**Careful study of the $\tau^- \to K_S^0\pi^-\nu_\tau$ near the $K_S^0\pi$ production threshold is needed**

# $K^*(892)^\pm$ mass and width (I)

Model uncertainties in $K^*(892)^\pm$ mass and width are evaluated from approximations with the following models:
$K_0^*(800)+K^*(892)+K^*(1410)$, $K_0^*(800)+K^*(892)+K_0^*(1430)$,
$K_0^*(800)+K^*(892)+K^*(1680)$, $K^*(892)$+LASS.

| | $M(K^*(892)),\ \mathrm{MeV}/c^2$ | $\Gamma(K^*(892)),\ \mathrm{MeV}$ |
|---|---|---|
| This work | $895.47 \pm 0.20_{\mathrm{stat}} \pm 0.44_{\mathrm{syst}} \pm 0.59_{\mathrm{mod}}$ | $46.2 \pm 0.6_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}} \pm 0.7_{\mathrm{mod}}$ |
| PDG-2017 | $891.76 \pm 0.25$ | $50.3 \pm 0.8$ |
| Difference | $3.71 \pm 0.80$ | $-4.1 \pm 1.7$ |

**PDG average is based on the results from the fixed target experiments**



| | | | | | | |
|---|---|---|---|---|---|---|
| 894.3 ±1.5 | 1150 | [2,3] CLARK | 73 | HBC | – | 3.3 $K^- p \to \overline{K}^0 \pi^- p$ |
| 892.0 ±2.6 | 341 | [2] SCHWEING...68 | | HBC | – | 5.5 $K^- p \to \overline{K}^0 \pi^- p$ |

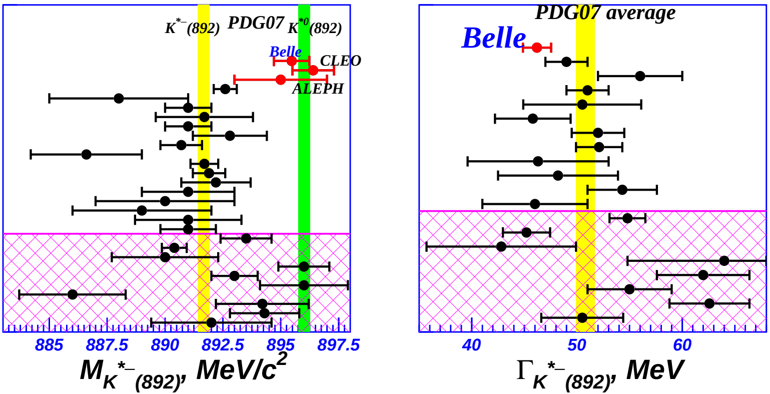
**CHARGED ONLY, PRODUCED IN $\tau$ LEPTON DECAYS**

| *VALUE* (MeV) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **895.47±0.20±0.74** | 53k | [6] EPIFANOV | 07 | BELL | $\tau^- \to K_S^0 \pi^- \nu_\tau$ |

• • • We do not use the following data for averages, fits, limits, etc. • • •

| | | | | | |
|---|---|---|---|---|---|
| 895.3 ±0.2 | | [7,8] JAMIN | 08 | RVUE | $\tau^- \to K_S^0 \pi^- \nu_\tau$ |
| 896.4 ±0.9 | 11970 | [9] BONVICINI | 02 | CLEO | $\tau^- \to K^- \pi^0 \nu_\tau$ |
| 895 ±2 | | [10] BARATE | 99R | ALEP | $\tau^- \to K^- \pi^0 \nu_\tau$ |

# $K^*(892)^\pm$ mass and width (II)



The $K^*(892)^-$ width is compatible with the previous measurements within experimental errors, however the $K^*(892)^-$ mass value obtained in $\tau^- \to K^0_S\pi^-\nu_\tau$ is systematically higher than those before and is consistent with the world average value of the neutral $K^*(892)^0$ mass. None of the previous measurements in PDG, all of which were performed more than 30 years ago, present the systematic uncertainties for their measurements.

# CPV in hadronic $\tau$ decays at $B$ factories

- CPV has not been observed in lepton decays
- It is strongly suppressed in the SM ($A^{\rm CP}_{\rm SM} \lesssim 10^{-12}$) and observation of large CPV in lepton sector would be clean sign of New Physics
- $\tau$ lepton provides unique possibility to search for CPV effects, as it is the only lepton decaying to hadrons, so that the associated strong phases allows us to visualize CPV in hadronic $\tau$ decays.

**I. CPV in $\tau^- \to \pi^- K_S (\geq 0\pi^0)\nu_\tau$ at BaBar (Phys. Rev. D 85, 031102 (2012))**

Data sample of $\int L dt = 476$ fb$^{-1}$ was analyzed

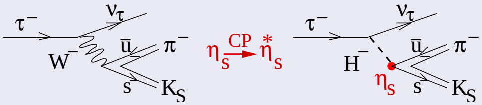
$$A_{\rm CP} = \frac{\Gamma(\tau^+ \to \pi^+ K^0_S(\geq 0\pi^0)\bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K^0_S(\geq 0\pi^0)\nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K^0_S(\geq 0\pi^0)\bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K^0_S(\geq 0\pi^0)\nu_\tau)} = (-0.36 \pm 0.23 \pm 0.11)\%$$

**$2.8\sigma$ deviation** from the SM expectation: $A^{K^0}_{\rm CP} = (+0.36 \pm 0.01)\%$

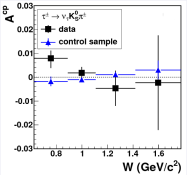
**II. CPV in $\tau^- \to K^0_S \pi^- \nu_\tau$ at Belle (Phys. Rev. Lett. 107, 131801 (2011))** $\int$Ldt=699 fb$^{-1}$

Angular distributions were analyzed, $A_{\rm CP}(W = M_{K_S\pi})$ was measured ($d\omega = d\cos\beta \, d\cos\theta$):

$$A_{\rm CP}(W) = \frac{\int \cos\beta \cos\psi \left( \frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega} \right) d\omega}{\frac{1}{2}\int \left( \frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega} \right) d\omega} \simeq \langle \cos\beta \cos\psi \rangle_{\tau^-} - \langle \cos\beta \cos\psi \rangle_{\tau^+}$$



$|Im(\eta_S)| < 0.026$



# Further studies at *B* factories (I)

- To elucidate the nature of the $K^*(892)^- - K^*(892)^0$ mass difference it is suggested to study: $\tau^- \to K^0_S\pi^-\nu_\tau$, $\tau^- \to K^0_S\pi^-\pi^0\nu_\tau$, $\tau^- \to K^0_S K^-\pi^0\nu_\tau$.
  - $K^*(892)^-$ mass and width can be measured in the clean experimental conditions without disturbance from the final state interactions in the $\tau^- \to K^0_S\pi^-\nu_\tau$ decay.
  - Study of the $\tau^- \to K^0_S\pi^-\pi^0\nu_\tau$ mode allows one to measure simultaneously in one mode the $K^*(892)^-(K^0_S\pi^-)$ and the $K^*(892)^0(K^0_S\pi^0)$ masses in the case of one accompanying pion. 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.
  - It is possible to investigate precisely an effect of the pure hadronic interaction of the $K^*(892)^-(K^*(892)^0)$ and $K^0_S(K^-)$ on the $K^*(892)^-(K^*(892)^0)$ mass in the $\tau^- \to K^0_S K^-\pi^0\nu_\tau$ decay.
- In the analysis of the $\tau^- \to K^0_S\pi^-\nu_\tau$ decay, it is very desirable to measure separately vector ($W_B$), scalar ($W_{SA}$) form factors and the interference term ($W_{SF}$).
  - $K^*(892)^-$ mass and width are measured in the vector form factor (properly 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, $W_{SA}$, is important for the tests of the various fenomenological models and search for CPV.
  - The interference between vactor and scalar form factors, $W_{SF}$, is necessary in the search for CPV in $\tau^- \to K^0_S\pi^-\nu_\tau$ decay.
- **A complete study of the hadronic $\tau$ decays into $\geq 3$ hadrons can be done in the full multidimensional phase-space of the reaction** $\boldsymbol{e^+e^- \to (\tau^- \to \mathrm{hadrons}^-\nu_\tau;\ \tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau)}$ **or** $\boldsymbol{e^+e^- \to (\tau^- \to \mathrm{hadrons}^-\nu_\tau;\ \tau^+ \to \rho^+\bar{\nu}_\tau)}$

# Further studies at *B* factories (II)

The parametrization of the hadronic current in the $\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$ decay was established by CLEO in their unbinned analysis of the $e^+e^- \to (\tau^- \to \pi^-\pi^0\pi^0\nu_\tau,\ \tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau)$ process in the full phase space: D. M. ASNER *et al.* [CLEO], PHYS. REV. D **61**, 012002 (2000).

$$J^\mu = \beta_1 j_1^\mu(\rho\pi^0)_{S-wave} + \beta_2 j_2^\mu(\rho'\pi^0)_{S-wave} + \beta_3 j_3^\mu(\rho\pi^0)_{D-wave} + \beta_4 j_4^\mu(\rho'\pi^0)_{D-wave} +$$
$$+\beta_5 j_5^\mu(f_2(1270)\pi)_{P-wave} + \beta_6 j_6^\mu(f_0(500)\pi)_{P-wave} + \beta_7 j_7^\mu(f_0(1370)\pi)_{P-wave}$$

- Before studying hadronic decays, leptonic decay should be analyzed (measurement of Michel parameters) to develop the fitter and polish the procedure (CLEO studied $\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$ after they measured Michel parameters).
- At Belle we are now finalizing the measurement of Michel parameters.
- The developed procedure can be used to study dynamics of the $(\tau^\mp \to (K\pi)^\mp\nu\ ;\ \tau^\pm \to \rho^\pm\nu)$ and $(\tau^\mp \to (K\pi)^\mp\nu\ ;\ \tau^\pm \to \ell^\pm\nu\nu)$ processes and to search for CPV in $\tau^- \to (K\pi)^-\nu_\tau$ (also in the spin-dependent part of the differential decay width).

# Further studies at *B* factories (III)

Analysis of the $(\tau^{\mp} \to (K\pi)^{\mp}\nu\,;\ \tau^{\pm} \to \rho^{\pm}\nu)$ events, search for CPV in $\tau^{-} \to (K\pi)^{-}\nu_{\tau}$.

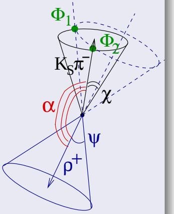
**The analysis of the decay products of both taus allows one to constrain direction of $\tau^{-} - \tau^{+}$ axis. Such a constraint is efficient to suppress background from $\tau^{-} \to (K\pi)^{-}K_L^0\nu_{\tau}$.**

$$\frac{d\sigma(\vec{\zeta}^{*},\vec{\zeta'}^{*})}{d\Omega_{\tau}} = \frac{\alpha^2}{64E_{\tau}^2}\beta_{\tau}(D_0 + D_{ij}\zeta_i^{*}\zeta_j'^{*}), \quad \frac{d\Gamma(\tau^{\pm}(\vec{\zeta'}^{*}) \to \rho^{\pm}\nu)}{dm^2_{\pi\pi}d\Omega^{*}_{\rho}d\tilde{\Omega}_{\pi}} = A' \mp \vec{B'}\vec{\zeta'}^{*}$$

$$\frac{d\Gamma(\tau^{\mp}(\vec{\zeta}^{*}) \to (K\pi)^{\mp}\nu)}{dm^2_{K\pi}d\Omega^{*}_{K\pi}d\tilde{\Omega}_{\pi}} = \begin{array}{l} (A_0 + \eta_{CP}A_1) + (\vec{B}_0 + \eta_{CP}\vec{B}_1)\vec{\zeta}^{*} \\ (A_0 + \eta^{*}_{CP}A_1) - (\vec{B}_0 + \eta^{*}_{CP}\vec{B}_1)\vec{\zeta}^{*} \end{array}$$

$$\frac{d\sigma((K\pi)^{\mp},\rho^{\pm})}{dm^2_{K\pi}d\Omega^{*}_{K\pi}d\tilde{\Omega}_{\pi}dm^2_{\pi\pi}d\Omega^{*}_{\rho}d\tilde{\Omega}_{\pi}d\Omega_{\tau}} = \frac{\alpha^2\beta_{\tau}}{64E_{\tau}^2}\begin{pmatrix} \mathcal{F} + \eta_{CP}\mathcal{G} \\ \mathcal{F} + \eta^{*}_{CP}\mathcal{G} \end{pmatrix}$$

$$\mathcal{F} = D_0A_0A' - D_{ij}B_{0i}B'_j,\ \mathcal{G} = D_0A_1A' - D_{ij}B_{1i}B'_j$$



$$\frac{d\sigma((K\pi)^{\mp},\rho^{\pm})}{dp_{K\pi}d\Omega_{K\pi}dm^2_{K\pi}d\tilde{\Omega}_{\pi}dp_{\rho}d\Omega_{\rho}dm^2_{\pi\pi}d\tilde{\Omega}_{\pi}} = \sum_{\Phi_1,\Phi_2}\frac{d\sigma((K\pi)^{\mp},\rho^{\pm})}{dm^2_{K\pi}d\Omega^{*}_{K\pi}d\tilde{\Omega}_{\pi}dm^2_{\pi\pi}d\Omega^{*}_{\rho}d\tilde{\Omega}_{\pi}d\Omega_{\tau}}\left|\frac{\partial(\Omega^{*}_{K\pi},\Omega^{*}_{\rho},\Omega_{\tau})}{\partial(p_{K\pi},\Omega_{K\pi},p_{\rho},\Omega_{\rho})}\right|$$

$\eta_{\mathrm{CP}}$ **is extracted in the simultaneous unbinned maximum likelihood fit of the** $((K\pi)^{-},\rho^{+})$ **and** $((K\pi)^{+},\rho^{-})$ **events in the 12D phase space.**

# Summary

- **The world largest statistics of $\tau$ leptons collected by Belle and *BABAR* opens new era in the precision tests of the Standard Model, search for the effects of New Physics and precision studies of low energy QCD**
- Belle and *BABAR* essentially improved the accuracy of the branching fractions of $\tau^- \to (K\pi)^-\nu_\tau$ decays:
  $\boldsymbol{\mathcal{B}(\tau^- \to K^0_S\pi^-\nu_\tau) = (4.16 \pm 0.01 \pm 0.08) \times 10^{-3}}$ **(Belle)**
  $\boldsymbol{\mathcal{B}(\tau^- \to K^-\pi^0\nu_\tau) = (4.16 \pm 0.03 \pm 0.18) \times 10^{-3}}$ **(*BABAR*)**
- At Belle the $K^0_S\pi$ invariant mass spectrum was studied. The $K^*(892)$ alone is not sufficient to describe the $K^0_S\pi$ 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. There is large systematic uncertainty in the near $K^0_S\pi$ production threshold part of the spectrum due to the large background from the $\tau^- \to K^0_S\pi^-K^0_L\nu_\tau$ decay, whose dynamics is not precisely known. In the new study it will be possible to suppress this background essentially applying special kinematical constraints.
- For the first time the the $K^*(892)^-$ mass and width have been measured in $\tau$ 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. **Future high precision measurements of the $\boldsymbol{K^*(892)^-}$ parameters at GlueX are necessary to clarify this discrepancy.**
- Simulataneous study of the $\tau^- \to K^0_S\pi^-\nu_\tau$, $\tau^- \to K^0_S\pi^-\pi^0\nu_\tau$ and $\tau^- \to K^0_SK^-\pi^0\nu_\tau$ decays at the $B$ factories as well as the $e^+e^- \to K^0_SK^\pm\pi^\mp$ reaction at the VEPP-2000 could provide additional valuable information about the $K^*(892)^-$ mass, namely unveil an impact of the hadronic and electromagnetic interactions in the final state.
- The unbinned analysis of the reaction $e^+e^- \to (\tau^- \to \mathrm{hadrons}^-\nu_\tau;\ \tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau)$ or $e^+e^- \to (\tau^- \to \mathrm{hadrons}^-\nu_\tau;\ \tau^+ \to \rho^+\bar{\nu}_\tau)$ in the full miltidimensional phase space opens the fruitful possibility for the comprehensive investigation of the dynamics of hadronic $\tau$ decays. It is very acute for the improved searches for the CPV violation in hadronic $\tau$ decays.