Feasibility study for a search for $\boldsymbol{\tau} \longrightarrow \boldsymbol{\mu}\gamma$ decay at Super $\mathbf{c} - \boldsymbol{\tau}$ factory

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Plan

Feasibility study for a search for $\tau \longrightarrow \mu\gamma$ decay at Super $\mathbf{c}-\tau$ factory

1. Motivation
2. Simulation
3. Selection criteria
4. Results

Study of $\tau^- \longrightarrow \mathbf{h}^-\mathbf{h}^+\mathbf{h}^-\nu_\tau$ decays at Belle

1. Introduction
2. Selection criteria
3. Hadron dynamics
4. Summary

Motivation

SCTF[a] - e^+e^- collider and general purpose 4π detector with longitudinal magnetic field.
$2E_b = 2 \div 5$ GeV, $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1}, 10 years , 10 ab^{-1}, $N_{\tau^+\tau^-} = 2.5 \times 10^{10}$

Physical programme

1. Studies of charmonium states
2. Spectroscopy of states of light quarks
3. Physics of D mesons
4. Physics of charmed baryons
5. τ lepton physics
6. Measurement of $\sigma_{e^+e^- \to hadrons}$
7. Two-photon physics

[a] Super charm tau factory. Conceptual design report. (2011).

Recalculation from neutrino oscillation data[a] gives $\mathcal{B}_{\tau\to\mu\gamma} \sim 10^{-54}$. At the Super B factories a limit scales as $1/\sqrt{N_{\tau^+\tau^-}}$ (ISR background). The limit on $\mathcal{B}_{\tau\to\mu\gamma} \sim (2 \div 3) \times 10^{-9}$ at SBF[b] (PDG limit[c] today is 4.4×10^{-8}). But at SCTF ISR background is vanishingly small.
A search for $\tau \to \mu\gamma$ is complicated task and this is suitable for detector optimization.
All systems are important for this problem: track system, PID system, calorimeter and muon system. Special sophisticated PID system is Focusing Aerogel RICH [d] for μ/π separation up to 1 $\frac{GeV}{c}$ or $\frac{\delta u}{u} \sim 10^{-3}$.

[a] Rev. of Nucl. And Part. Science 2008 58 p.315q

[b] SuperB Progress Reports – Physics. SuperB Collaboration.

[c] Phys.Rev.Lett. **104** (2010) 021802.

Simulation

1. fast simulation
2. energy resolution 1.5% and 2.5% @ 1GeV
3. coordinate resolution of calorimeter - 1 cm
4. acceptance $20^\circ < \Theta < 160^\circ$
5. threshold of photons detection 20 MeV
6. momentum resolution 0.4% @ 1GeV/c
7. efficiency 100%
8. particle identification is not simulated
9. background - $e^+e^- \to \tau^+\tau^-$ pairs decays
   $(\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau; \tau^+\tau^- \to \mu^+\bar{\nu}_\tau\nu_\mu\pi^-\pi^0\nu_\tau; \tau^+\tau^- \to \pi^+\bar{\nu}_\tau\pi^-\pi^0\pi^0\nu_\tau\nu_\mu$
   etc.)

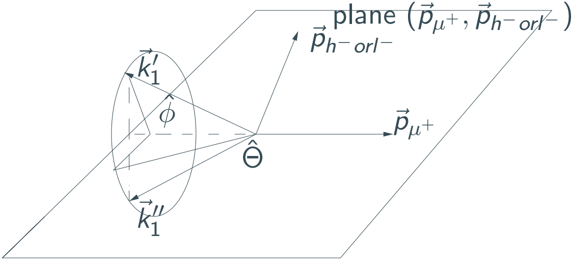
Selection criteria

$\Delta E = E_\mu + \omega - E_b$
$m_{bc} = \sqrt{E_b^2 - (\vec{p}_\mu + \vec{k})^2}$
$m_{vis} = \sqrt{(E_\mu + \omega)^2 - (\vec{p}_\mu + \vec{k})^2}$
$E_{miss} = 2E_b - E_\mu - \omega - E_{tag}$
$m_{miss}^2 = E_{miss}^2 - \vec{p}_{miss}^2$

The energy of the signal photon is used in all standard selection criteria, which include a signature of signal.

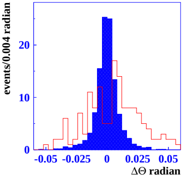
For decay $\tau \to l\gamma$ it's possible to reconstruct signal gamma using l and hadron system from tagging τ. The same way as neutrino reconstruction for SM decays $\tau^+\tau^-$ (where both τ decay semileptonic)[a]. The equations have one free parameter $(m^2_{\nu\bar{\nu}})$ for leptonic decay of the tagging τ. The selection criteria are bazed on angle differences $\Delta\Theta, \Delta\phi$ do not contain energy of signal photon.

[a] J. H. Kühn, Phys, Lett. B **313** (1993) 458.

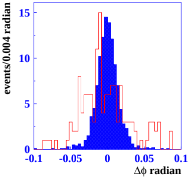


$$P_{e^+} + P_{e^-} = P_{\tau^+} + P_{\tau^-} = P_{\mu^+} + P_\gamma + P_{\tau^-} = P_{\mu^+} + P_\gamma + P_{h^- or l^-} + P_{\nu_\tau or \nu_\tau \bar{\nu}_l}$$
$$P_{e^+} + P_{e^-} = P_{\tau^+} + P_{\tau^-} = P_{h^+} + P_{\bar{\nu}_\tau} + P_{\tau^-} = P_{h^+} + P_{\bar{\nu}_\tau} + P_{h^- or l^-} + P_{\nu_\tau or \nu_\tau \bar{\nu}_l}$$

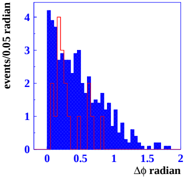
Signal is blue, background is red (arbitrary scale)



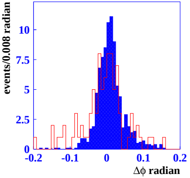
tagging mode $\pi^- \nu_\tau$



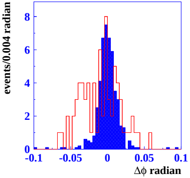
tagging mode $\pi^- \nu_\tau$



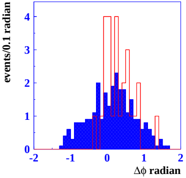
tagging mode $e^- \nu_\tau \bar{\nu}_\tau$



tagging mode $\pi^- \pi^0 \nu_\tau$



tagging mode $\pi^- \pi^- \pi^+ \nu_\tau$



tagging mode $\pi^- \pi^0 \pi^0 \nu_\tau$

Results

After summation of all points

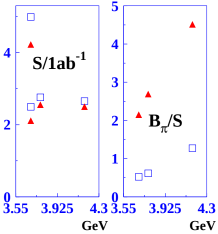
$10\ ab^{-1}$ $\mathcal{B}_{\tau\to\mu\gamma} = 10^{-9}$

$\frac{\sigma_E}{E} = 1.5\%$ $\frac{\sigma_E}{E} = 2.5\%$

$S = 21.2$ $S = 19.1$

$B = 11.5^{+1.5}_{-1.2}$ $B = 45.4^{+2.5}_{-1.7}$

Number of signal events (at $\mathcal{B}_{\tau\to\mu\gamma} = 10^{-9}$) for 1 ab^{-1} and background signal ratio for pions, squares – 1.5% triangles – 2.5% resolutions.



1. selection criteria without signal photon energy increase sensitivity by a factor of 3- 4
2. achievable limits for $\tau \to \mu\gamma$ are $\sim 2.5 \times 10^{-10}$ @ $\frac{\sigma_E}{E} = 2.5\%$ and $\sim 1.5 \times 10^{-10}$ @ $\frac{\sigma_E}{E} = 1.5\%$ (μ/π separation 1/10)
3. selection criteria without signal photon energy are useful for a search $\tau \to \mu\gamma, \tau \to e\gamma$ at SCTF and they may be useful for the same research at SBF

Plan

Study of $\boldsymbol{\tau}^- \longrightarrow \mathbf{h}^-\mathbf{h}^+\mathbf{h}^-\boldsymbol{\nu}_\tau$ decays at Belle

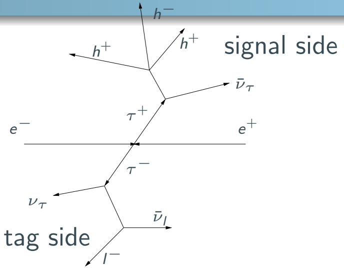
1. Introduction
2. Selection criteria
3. Hadron dynamics
4. Summary

1. Measurement of the branching fractions based on the full statistics
2. Study of the hadronic dynamics, attempt to improve the systematics, detailed analysis of the intermediate states
3. CP -violation search
4. A feasibility study of m_{ν_τ} measurement

Decay mode	units	Belle	Babar	PDG 2006
$\pi^-\pi^-\pi^+\nu_\tau(ex.K^0)$	10^{-2}	$8.42 \pm 0.003^{+0.26}_{-0.25}$ [1]	$8.83 \pm 0.01 \pm 0.13$ [2]	9.02 ± 0.08
$K^-\pi^-\pi^+\nu_\tau(ex.K^0)$	10^{-3}	$3.3 \pm 0.01^{+1.6}_{-1.7}$ [1]	$2.73 \pm 0.02 \pm 0.09$ [2]	3.33 ± 0.5
$\pi^-K^-K^+\nu_\tau$	10^{-3}	$1.55 \pm 0.01^{+0.06}_{-0.05}$ [1]	$1.346 \pm 0.01 \pm 0.036$ [2]	1.54 ± 0.09
$K^-K^-K^+\nu_\tau$	10^{-5}	$3.29 \pm 0.17^{+0.19}_{-0.20}$ [1]	$1.58 \pm 0.13 \pm 0.12$ [2]	< 3.7
$\pi^-\phi\nu_\tau$	10^{-5}		$3.42 \pm 0.55 \pm 0.25$ [2]	< 20
$K^-\phi\nu_\tau$	10^{-5}	$4.05 \pm 0.25 \pm 0.26$ [3]	$3.39 \pm 0.20 \pm 0.28$ [2]	< 6.7
$K^-K^-K^+\nu_\tau(ex.\phi)$	10^{-6}		< 2.5 [2]	

[1] PhysRevD.81.113007 (2010); 666fb^{-1}
[2] Phys.Rev.Lett. 100 (2008) 011801; 342fb^{-1}
[3] Physics Letters B643 (2006); 401fb^{-1}

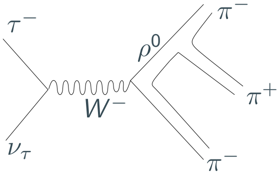
Selection criteria



1. 4-track events from tauskim
2. Zero charge, without K_S π^0
3. lepton (μ, e) and three hadrons
4. $Pr(K) > 0.75, Pr(l) > 0.7$
5. $E_{extra} > 0.2 GeV$

1. $max[\frac{P_t}{GeV/c}] > 0.5$
2. $7 > \frac{m_{miss}}{GeV/c^2} > 1$
3. $v_r < 0.5$ cm $|v_z| < 2.5$ cm
4. $150^\circ > \Theta^{c.m.s.}_{miss} > 30^\circ$
5. $\Theta^{c.m.s.}_{hadrons/lepton} > 90^\circ$

We use TAUOLA generator. Tau decays into three pseudoscalar hadrons and tau-neutrino are described with four form factors.
TAUOLA generator uses the quasi two-body model. It allows to parametrize F_s, F_v, F_1, F_2 form factors.
There are many intermediate states available for $h^- h^+ h^- \nu_\tau$.
$\pi^- \pi^+ \pi^- \nu_\tau$ $(\rho\pi, \rho'\pi, f_0\pi, f_2\pi)$
$K^- \pi^+ \pi^- \nu_\tau$ $(\rho K, K^\star \pi)$
$K^- K^+ \pi^- \nu_\tau$ $(\bar{K}^\star K, \phi\pi)$
$K^- K^+ K^- \nu_\tau$ (ϕK)



However, not all intermediate states, observed in the experiments are included now in this generator $(\phi\pi^-, \phi K^-, \rho K^-)$.

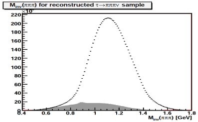
$$\langle h_1 h_2 h_3 \mid H^\mu \mid 0 \rangle = F_s(m_{12}^2, m_{13}^2, Q^2) Q^\mu + \{F_1(m_{12}^2, m_{13}^2, Q^2)(p_1 - p_2)_\nu + F_2(m_{12}^2, m_{13}^2, Q^2)(p_2 - p_3)_\nu\}(g^{\mu\nu} - \frac{Q^\mu Q^\nu}{Q^2}) + iF_v(m_{12}^2, m_{13}^2, Q^2)\epsilon^{\mu\nu\rho\sigma} p_{1\nu} p_{2\rho} p_{3\sigma}$$

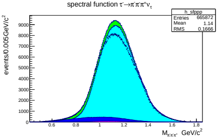
Where $Q = p_1 + p_2 + p_3$, F_s - pseudoscalar, F_1, F_2- pseudovector, F_v - vector form factors.

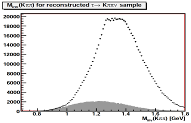
Comparison of the spectral function

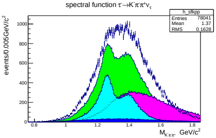
cyan - signal, magenta - background from 3-prong, blue - other background, green - total, open - experiment

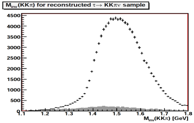
PhysRevD.81.113007 (2010) 80 fb^{-1} simulation only $\tau^+\tau^-$ events

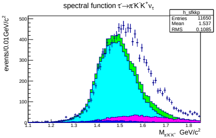


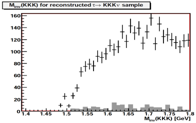


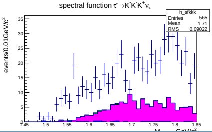






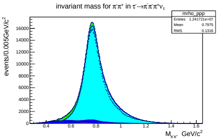


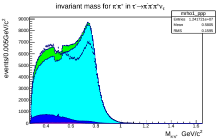


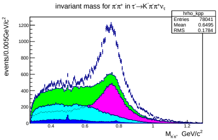


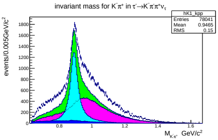
Invariant mass of the pair of mesons

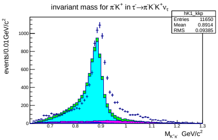
cyan - signal, magenta - background from 3-prong, blue - other background, green - total, open - experiment

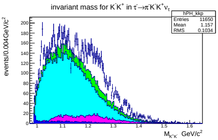


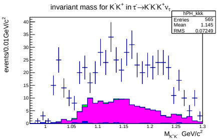


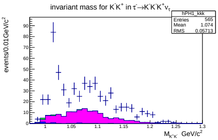












Results

1. First step of this analysis has been done
2. Preliminary selection criteria were developed and applied to the data
3. TAUOLA generator does not include some intermediate states

Plans

1. Absolute branching fraction measurement
2. Study of the hadron dynamics

Thank you very much for inviting me

to this conference

$$P = p_1 + k_1 + p_2 + t_2$$
$$(p_1 + k_1)^2 = (p_2 + t_2)^2 = m_\tau^2$$
$$k_1^2 = 0, t_2^2 = m_q^2$$
$$k_1 P = \frac{P^2}{2} - P p_1$$
$$k_1 p_1 = \frac{m_\tau^2 - m_1^2}{2}$$
$$k_1 p_2 = \frac{m_q^2 - m_\tau^2 - m_2^2 + 2(P - p_1) p_2}{2}$$
$$k_1 = \frac{[\{A p_{1\theta} p_{2\delta} + B p_{2\theta} P_\delta + C P_\theta p_{1\delta}\}\epsilon^{\mu\theta\delta\psi} + D g^{\mu\psi}]\epsilon_{\nu\phi\pi\psi} P^\nu p_1^\phi p_2^\pi}{\epsilon^{\alpha\beta\gamma\rho}\epsilon_{\alpha_1\beta_1\gamma_1\rho} P_\alpha p_{1\beta} p_{2\gamma} P^{\alpha_1} p_1^{\beta_1} p_2^{\gamma_1}}$$
$$k_1 P = A \; k_1 p_1 = B \; k_1 p_2 = C$$
$$k_1^2 \propto A^2[-m_1^2 m_2^2 + (p_1 p_2)^2] + 2AB[-(p_1 p_2)(P p_2) + (p_1 P) m_2^2] +$$
$$B^2[-P^2 m_2^2 + (P p_2)^2] + +2BC[-(P p_1)(P p_2) + (p_1 p_2) P^2] +$$
$$2AC[-(p_1 p_2)(P p_1) + (p_2 P) m_1^2] + C^2[-P^2 m_1^2 + (P p_1)^2] + D^2 = 0$$

$$Cos\hat{\Theta} = \frac{Pp_1(P^2/2 - Pp_1) - P^2(m_\tau^2 - m_1^2)/2}{\sqrt{\{Pp_1\}^2 - m_1^2 P^2 (P^2/2 - Pp_1)}}.$$

$$Cos\Theta = \frac{-k_1 p_1 + k_1 P P p_1 / P^2}{\sqrt{(\{Pp_1\}^2/P^2 - m_1^2)(k_1 P)^2/P^2}}$$

$$\sqrt{1 - \cos^2\hat{\Theta}}\cos\hat{\phi} =$$

$$\frac{m_q^2 - m_\tau^2 - m_2^2 + Pp_2 - p_1 p_2 + Pp_2 Pp_1/P^2 - (P^2 p_1 p_2 - Pp_2 Pp_1)m_\tau^2/P^2 m_1^2}{2\sqrt{(-m_2^2 + {Pp_2}^2/P^2 + \{p_1 p_2 - Pp_1 Pp_2/P^2\}^2/m_1^2)(\{P^2/2 - Pp_1\}^2/P^2)}}$$

$$\sqrt{1 - \cos^2\Theta}\cos\phi =$$

$$\frac{k_1 p_2 - k_1 P P p_2/P^2 - (p_1 p_2 - Pp_2 Pp_1/P^2)k_1 p_1/m_1^2}{\sqrt{(-m_2^2 + {Pp_2}^2/P^2 + \{p_1 p_2 - Pp_1 Pp_2/P^2\}^2/m_1^2)\{k_1 P\}^2/P^2}}$$

$$\Delta\Theta = \hat{\Theta} - \Theta \quad \Delta\phi = \hat{\phi}(m_q^2 = 0) - \phi$$

Appendix

$\sqrt{s}$ GeV $\frac{\sigma_E}{E}$		3.686 1.5%	3.686 2.5%	3.77 1.5%	3.77 2.5%	4.17 1.5%	4.17 2.5%
$\pi^- \nu_\tau$	S	3.1	2.7	3.0	2.8	3.2	2.7
	B	2.5 ± 0.4	8.2 ± 0.7	2.7 ± 0.4	10.1 ± 0.4	4.5 ± 0.9	12.5 ± 0.8
$\pi^- \pi^0 \nu_\tau$	S	6.9	5.5	6.7	5.9	6.5	6.1
	B	9.0 ± 1.4	30 ± 2	8.3 ± 1.3	35 ± 2	11.5 ± 1.6	42 ± 2
$\mu^- \bar{\nu}_\mu \nu_\tau$	S	8.8	7.9	8.5	7.8	5.6	5.5
	B	2.2 ± 0.5	6.3 ± 0.7	2.9 ± 0.5	12.3 ± 1.0	6.8 ± 0.8	23.2 ± 1.4
$e^- \bar{\nu}_e \nu_\tau$	S	9.0	7.5	8.4	7.9	5.1	5.1
	B	1.6 ± 0.5	10.0 ± 0.9	3.3 ± 0.5	13.4 ± 1.1	6.1 ± 0.7	19.9 ± 1.3
$\pi^- \pi^0 \pi^0 \nu_\tau$	S	1.6	1.2	1.6	1.4	1.6	1.5
	B	1.0 ± 0.2	2.4 ± 0.3	1.0 ± 0.3	3.8 ± 0.5	1.5 ± 0.3	3.8 ± 0.5
$\pi^- \pi^+ \pi^- \nu_\tau$	S	2.6	2.3	2.5	2.6	1.9	1.7
	B	0.5 ± 0.2	1.4 ± 0.3	0.8 ± 0.2	1.8 ± 0.3	0.6 ± 0.2	2.0 ± 0.3