BELLE

LHCb

東京大学
THE UNIVERSITY OF TOKYO

Tau lifetime and decays

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Outline:

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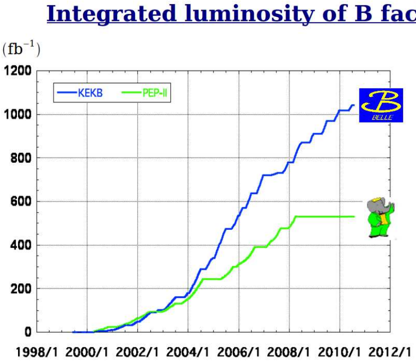
Introduction

- The world largest statistics of τ leptons collected by e^+e^- B-factories (Belle and BaBar) and LHCb opens new era in the precision tests of the Standard Model (SM).
- Basic tau properties, like: lifetime, mass, couplings, electric dipole moment, anomalous magnetic dipole moment and other appear as free parameters in the SM (mass), which should be measured experimentally as precise as possible, or provide unique possibility to test SM and search for the effects of New Physics (anomalous magnetic moment).
- In the SM τ 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 τ offer unique tools for the precision study of low energy QCD.

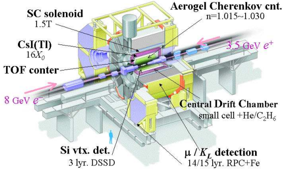
Introduction: B-factories (Belle and BaBar)


Integrated luminosity of B factories

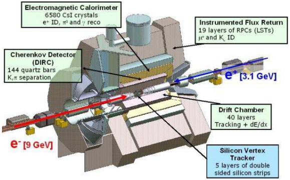
> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

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

Belle Detector



BABAR detector



$$\sigma(b\bar{b}) = 1.1 \text{ nb } N_{b\bar{b}} = 1.3 \times 10^9$$
$$\sigma(c\bar{c}) = 1.3 \text{ nb } N_{c\bar{c}} = 2.0 \times 10^9$$
$$\sigma(\tau\tau) = 0.9 \text{ nb } N_{\tau\tau} = 1.4 \times 10^9$$

B-factories are also charm- and τ-factories !

B-factory experimental strategy is proved to be fruitful to search for New Physics.

Precision studies of τ properties at B-factories

- **Tau lifetime:**

  Belle: $\tau_\tau = (290.17 \pm 0.53(\mathrm{stat}) \pm 0.33(\mathrm{syst}))$ fs; PRL 112, 031801 (2014)

  BaBar(prelim.): $\tau_\tau = (289.40 \pm 0.91(\mathrm{stat}) \pm 0.90(\mathrm{syst}))$ fs; Nucl. Phys. B 144, 105 (2005)

- Tau mass:
  Belle: $m_\tau = (1776.61 \pm 0.13(\mathrm{stat}) \pm 0.35(\mathrm{syst}))$ MeV/c^2; PRL 99, 011801 (2007)
  BaBar: $m_\tau = (1776.68 \pm 0.12(\mathrm{stat}) \pm 0.41(\mathrm{syst}))$ MeV/c^2; PRD 80, 092005 (2009)
  Accuracy comparable with the most precision measurements done by **KEDR** and **BES** at the $\tau^+\tau^-$ production threshold.

- Tau electric dipole moment (EDM):
  Belle: $\mathrm{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$ e·cm, $\mathrm{Im}(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17}$ e·cm; PLB 551, 16 (2003) ($\int Ldt = 29.5$ fb^{-1}) We are working on EDM with full statistics

- Hadronic contribution to a_μ ($\tau^- \to \pi^-\pi^0\nu_\tau$):
  Belle: $a_\mu^{\pi\pi} = (523.5 \pm 1.1(\mathrm{stat}) \pm 3.7(\mathrm{syst})) \times 10^{-10}$; PRD 78, 072006 (2008)

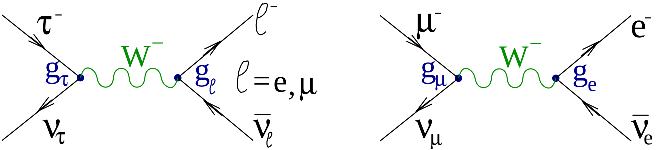
- Lepton universality:
  BaBar: $\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020$, $\left(\frac{g_\tau}{g_\mu}\right)_\mathrm{h} = 0.9850 \pm 0.0054$, h=$\pi$, K;
  PRL 105, 051602 (2010)

- Michel parameters in $\tau \to \ell\nu\nu(\gamma)$ (ρ, η, ξ, δ, $\bar{\eta}$, κ):
  Belle: study is going on.

- Anomalous magnetic moment of τ (a_τ):
  - In $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau\gamma$ it is not so promising to measure a_τ at B-factories (see the talk: D. Epifanov "Tau physics at Super B-factory" at KEK-FF2014 Workshop).
  - Technique to measure a_τ in $e^+e^- \to \tau^+\tau^-$ process is under discussion.

Measurement of the τ-lepton lifetime, motivation

Precise measurement of the tau lifetime is necessary for the tests of lepton universality in the SM: $g_e = g_\mu = g_\tau$



$$\Gamma(L^- \to \ell^- \bar\nu_\ell \nu_L(\gamma)) = \frac{\mathcal{B}(L^- \to \ell^- \bar\nu_\ell \nu_L(\gamma))}{\tau_L} = \frac{g_L^2 g_\ell^2}{32 M_W^4} \frac{m_L^5}{192\pi^3} F_{\rm corr}(m_L, m_\ell)$$

$$F_{\rm corr}(m_L, m_\ell) = f(x)\left(1 + \frac{3}{5}\frac{m_L^2}{M_W^2}\right)\left(1 + \frac{\alpha(m_L)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right)$$

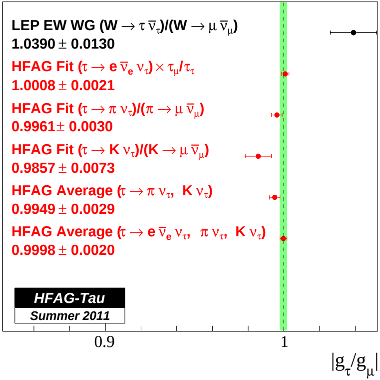
$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x,\ x = m_\ell / m_L$$

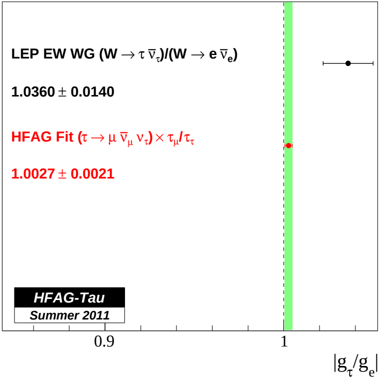
$$\mathcal{B}(\mu^- \to e^- \bar\nu_e \nu_\mu(\gamma)) = 1$$

$$\frac{g_\tau}{g_e} = \sqrt{\mathcal{B}(\tau^- \to \mu^- \bar\nu_\mu \nu_\tau(\gamma)) \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\rm corr}(m_\mu, m_e)}{F_{\rm corr}(m_\tau, m_\mu)}},\quad \frac{\mathbf{g}_\tau}{\mathbf{g_e}} = \mathbf{1.0024 \pm 0.0021}\ \text{(HFAG2012)}$$

$$\frac{g_\tau}{g_\mu} = \sqrt{\mathcal{B}(\tau^- \to e^- \bar\nu_\mu \nu_\tau(\gamma)) \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\rm corr}(m_\mu, m_e)}{F_{\rm corr}(m_\tau, m_e)}},\quad \frac{\mathbf{g}_\tau}{\mathbf{g}_\mu} = \mathbf{1.0006 \pm 0.0021}\ \text{(HFAG2012)}$$

Measurement of the τ-lepton lifetime, motivation





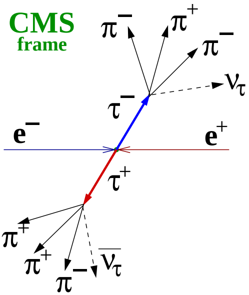
S. Schael *et al.* [ALEPH, DELPHI, L3, OPAL, LEP EWG]
Phys. Rep. 532, 119 (2013)

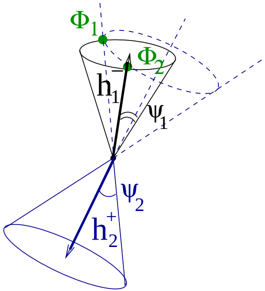
$$\frac{2\mathcal{B}(W \to \tau\nu_\tau)}{\mathcal{B}(W \to \mu\nu_\mu) + \mathcal{B}(W \to e\nu_e)} = 1.066 \pm 0.025$$

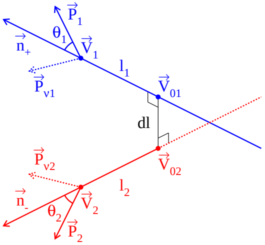
2.6σ **deviation from the Standard Model**

Measurement of τ_τ at Belle, method

We analyze $e^+e^- \to \tau^+\tau^- \to (\pi^+\pi^+\pi^-\bar{\nu}_\tau,\ \pi^+\pi^-\pi^-\nu_\tau)$ events.







$$\cos\psi_{1,2} = \frac{2E_\tau E_{h_{1,2}} - M_\tau^2 - m_{h_{1,2}}^2}{2p_\tau p_{h_{1,2}}}$$

$$x = \frac{\ell}{\beta_\tau\gamma_\tau}$$

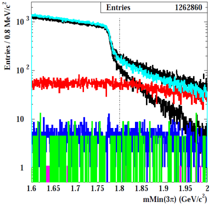
- τ momentum direction is determined with two-fold ambiguity in CMS, for the analysis we use the average axis.
- Asymmetric-energy layout of experiment allows us to determine $\tau^+\tau^-$ production point in LAB independently from the position of beam IP.
- Possibility to test CPT conservation measuring τ^- and τ^+ lifetimes separately.

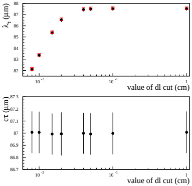
Measurement of τ_τ at Belle, selections

Use the data sample of $\int Ldt = 711$ fb^{-1} with $N_{\tau\tau} = 650 \times 10^6$

Selection criteria:

- Event is separated into two hemispheres in CMS, Thrust>0.9.
- Each hemisphere contains 3 charge pions with the ±1 net charge.
- There are no additional K^0_S, Λ, π^0 candidates. Number of additional photons $N_\gamma < 6$ with $E^{\mathrm{TOT}}_\gamma < 0.7$ GeV.
- $P_\perp(6\pi) > 0.5$ GeV/c, 4 GeV/$c^2 < M_{\mathrm{inv}}(6\pi) < 10.25$ GeV/c^2.
- Pseudomass $\sqrt{M_h^2 + 2(E_{\mathrm{beam}} - E_h)(E_h - P_h)} < 1.8$ GeV/c^2, $h = (3\pi)^-,\ (3\pi)^+$.
- Cuts on the quality parameters of the vertex fits and tau axis reconstruction.
- Minimal distance between τ^- and τ^+ axes in LAB $dl < 0.02$ cm.





1148360 events were selected with ~2% background contamination, the main background comes from $e^+e^- \to q\bar{q}$ ($q =$u, d, s).

Measurement of τ_τ at Belle, fit of decay length

Decay length PDF

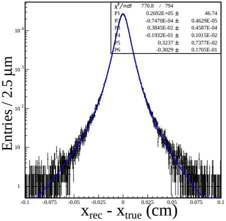
$$\mathcal{P}(x) = \mathcal{N}\int e^{-x'/\lambda_\tau} R(x-x';\vec{P})dx' + \mathcal{N}_{uds}R(x;\vec{P}) + \mathcal{P}_{cb}(x),$$

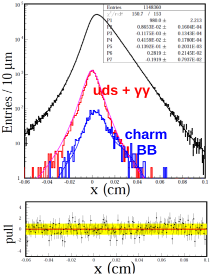
$$R(x;\vec{P}) = (1-2.5x)\cdot\exp\left(-\frac{(x-P_1)^2}{2\sigma^2}\right),$$

$$\sigma = P_2 + P_3|x-P_1|^{1/2} + P_4|x-P_1| + P_5|x-P_1|^{3/2}$$

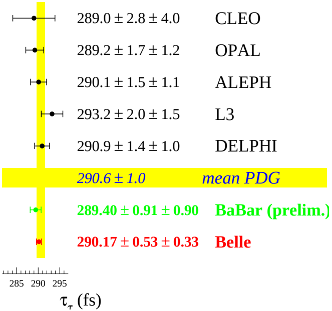
- Free parameters of the fit: $\lambda_\tau,\ \mathcal{N},\ \vec{P} = (P_1,\ldots,P_5)$
- λ_τ - estimator of $c\tau_\tau$, $c\tau_\tau = \lambda_\tau + \Delta_{\rm corr}$, $\Delta_{\rm corr}$ is determined from MC;
- $R(x;\vec{P})$ - detector resolution function;
- $\mathcal{N}_{uds}$ - contribution of background from $e^+e^- \to q\bar{q}\ (q=u,\ d,\ s)$ (predicted by MC)
- $\mathcal{P}_{cb}(x)$ - PDF for background from $e^+e^- \to q\bar{q}\ (q=c,\ b)$ (fixed from MC)

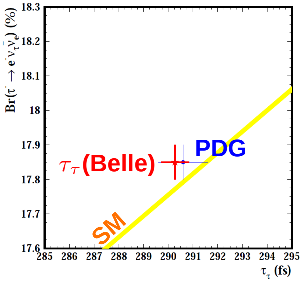
From the fit of experimental data
$\lambda_\tau = 86.53 \pm 0.16\ \mu$m, applying correction
$\Delta_{\rm corr} = 0.46\ \mu$m we got: $c\tau_\tau = 86.99 \pm 0.16\ \mu$m





Measurement of τ_τ at Belle, result





Systematic uncertainties

Source	**$\Delta c\tau$ (μm)**
Silicon vertex detector alignment	0.090
Asymmetry fixing	0.030
Fit range	0.020
Beam energy, ISR, FSR	0.024
Background contribution	0.010
τ-lepton mass	0.009
Total	**0.101**

$$c\tau_\tau = (86.99 \pm 0.16(\mathrm{stat}) \pm 0.10(\mathrm{syst}))\ \mu\mathrm{m}.$$

$$\tau_\tau = (290.17 \pm 0.53(\mathrm{stat}) \pm 0.33(\mathrm{syst}))\ \mathrm{fs}.$$

$$|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\mathrm{average}} < 7.0 \times 10^{-3}\ \mathrm{at}\ 90\%\ \mathrm{CL}.$$

Lepton universality

$$g_\tau/g_e = 1.0024 \pm 0.0021\ (\mathrm{HFAG2012})$$

$$\mathbf{g_\tau/g_e = 1.0031 \pm 0.0016}\ (\text{new Belle } \tau_\tau)$$

$$g_\tau/g_\mu = 1.0006 \pm 0.0021\ (\mathrm{HFAG2012})$$

$$\mathbf{g_\tau/g_\mu = 1.0013 \pm 0.0016}\ (\text{new Belle } \tau_\tau)$$

Hadronic τ decays

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

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

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

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

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

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 α_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 $\tau^- \to K_S^0 X^- \nu_\tau$ decays at Belle

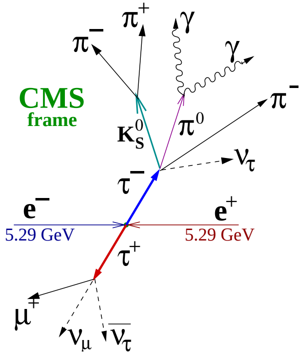
S. Ryu *et al.* [Belle Collaboration], Phys. Rev. D **89**, 072009 (2014)

Data sample of $\int Ldt = 669$ 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:

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

After the standard $\tau\tau$ preselection criteria we select events with particular configuration.

- Event is separated into two hemispheres in CMS, Thrust>0.9
- Tag side: 1-prong (e, μ or $\pi/K(n \geq 0)\pi^0$)
- Signal side:
  - $K_S^0 \to \pi^+\pi^-$:
    0.485 GeV/$c^2 < M_{\pi\pi} < 0.511$ GeV/c^2 ($\pm 5\sigma$),
    2 cm$< L_{K_S^0} < 20$ cm, $\Delta Z_{1,2} < 2.5$ cm
  - $\pi^0 \to \gamma\gamma$: $-6 < S_{\gamma\gamma}(= \frac{m_{\gamma\gamma} - m_{\pi^0}}{\sigma_{\gamma\gamma}}) < 5$
  - Charged kaon (pion):
    $\mathcal{P}_{K/\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_\pi + \mathcal{L}_K} > 0.7 (< 0.7)$
- $E_{\gamma extra}^{\rm LAB} < 0.2$ GeV



Calculation of branching fractions

Mode	$K_S^0 X^-$	$\pi^- K_S^0$	$K^- K_S^0$	$\pi^- K_S^0 \pi^0$	$K^- K_S^0 \pi^0$	$\pi^- K_S^0 K_S^0$	$\pi^- K_S^0 K_S^0 \pi^0$
$N^{\rm data}$	397806 ± 631	157836 ± 541	32701 ± 295	26605 ± 208	8267 ± 109	6684 ± 96	303 ± 33
ε_{det} (%)	9.66	7.09	6.69	2.65	2.19	2.47	0.82
$\frac{N^{\rm bg}}{N^{\rm data}}$ (%)	4.20 ± 0.46	8.86 ± 0.05	3.55 ± 0.07	5.60 ± 0.10	2.43 ± 0.10	7.89 ± 0.24	11.6 ± 1.60
$(\frac{\Delta\mathcal{B}}{\mathcal{B}})_{\rm syst}$(%)	2.4	2.5	4.0	3.9	5.2	4.4	8.1

The main non-$\tau\tau$ background comes from $e^+e^- \to q\bar{q}$ ($q = u,\ d,\ s,\ c$). To take into account cross-feed background 6 decay modes are analysed simultaneously:

$$N_i^{\rm sig} = \sum_j (\mathcal{E}^{-1})_{ij} (N_j^{\rm data} - N_j^{\rm bg})$$

For the $\pi^- K_S^0 \nu$, $K^- K_S^0 \nu$, $\pi^- K_S^0 \pi^0 \nu$ and $K^- K_S^0 \pi^0 \nu$ modes lepton tag is applied and normalisation to the two-lepton events ($\tau^\mp \to e^\mp \nu\nu,\ \tau^\pm \to \mu^\pm \nu\nu$) method is used to calculate branching fractions:

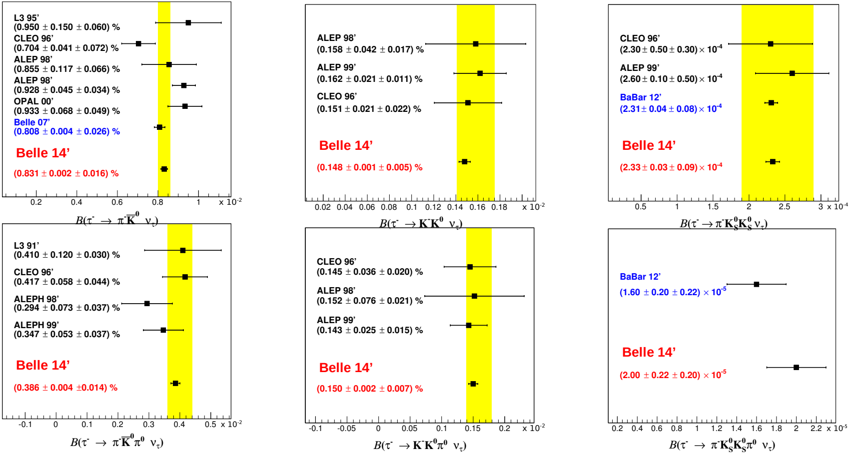
$$\mathcal{B}_i = \frac{N_i^{\rm sig}}{N_{e\text{-}\mu}^{\rm sig}} \frac{\mathcal{B}_e \mathcal{B}_\mu}{\mathcal{B}_e + \mathcal{B}_\mu}$$

To increase statistics for the remaining $\pi^- K_S^0 K_S^0 \nu$ and $\pi^- K_S^0 K_S^0 \pi^0 \nu$ modes 1-prong tag and luminosity normalisation method are used:

$$\mathcal{B}_i = \frac{N_i^{\rm sig}}{2\mathcal{L}\sigma_{\tau\tau}\mathcal{B}_{1-{\rm prong}}}$$

Result on branching fractions (Belle and BaBar)

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



Yellow bands show the world averages and their uncertainties from PDG:

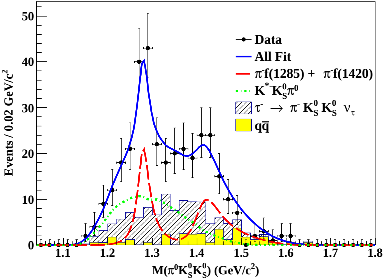
J. Beringer *et al.*, Phys. Rev. D **86**, 010001 (2012).

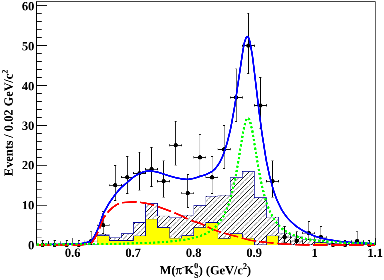
J. P. Lees *et al.* [BaBar Collaboration], Phys. Rev. D 86, 092013 (2012)

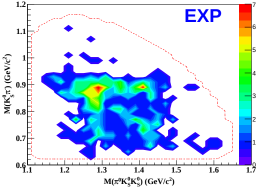
$$\mathcal{B}(\tau^- \to K^- K_S^0 K_S^0 \nu_\tau) < 6.3 \times 10^{-7} \text{ at 90\% CL}$$
$$\mathcal{B}(\tau^- \to K^- K_S^0 K_S^0 \pi^0 \nu_\tau) < 4.0 \times 10^{-7} \text{ at 90\% CL}$$

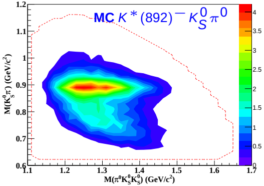
Study of $\tau^- \to \pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$ dynamics at Belle

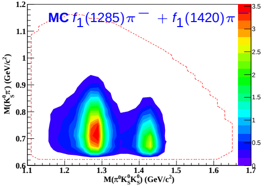
$f_1(1285)\pi^-$(34±5)% $\oplus$ $f_1(1420)\pi^-$(12±3)% $\oplus$ $K^*(892)^- K_S^0 \pi^0$(54±6)%









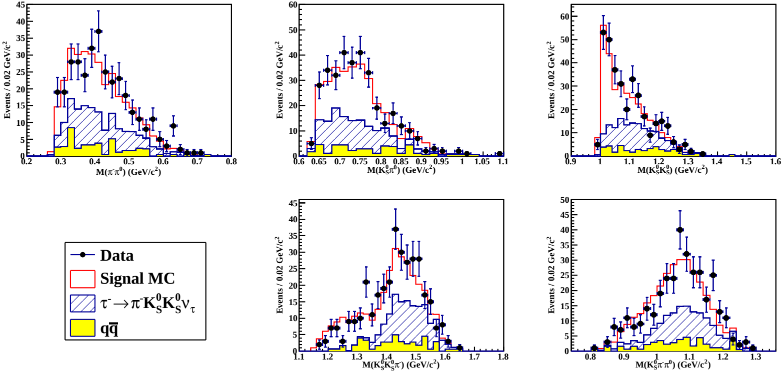


Simultaneous fit of $M_{\rm INV}(\pi^0 K_S^0 K_S^0)$($f_1(1285)$ and $f_1(1420)$) and $M_{\rm INV}(\pi^- K_S^0)$($K^*(892)^-$) distributions.

Obtained significances: $f_1(1285)(12\sigma)$, $f_1(1420)(4.8\sigma)$, $K^*(892)^-(7.8\sigma)$.

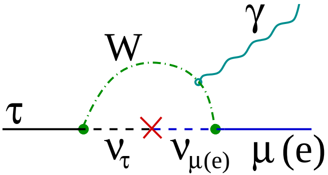
Study of $\tau^- \to \pi^- K^0_S K^0_S \pi^0 \nu_\tau$ dynamics at Belle

No other mechanisms were found for $\tau^- \to \pi^- K^0_S K^0_S \pi^0 \nu_\tau$



$$\begin{aligned}
\mathcal{B}(\tau^- \to f_1(1285)\pi^-\nu_\tau)\cdot\mathcal{B}(f_1(1285)\to K^0_S K^0_S \pi^0) &= (0.68 \pm 0.13 \pm 0.07)\times 10^{-5},\\
\mathcal{B}(\tau^- \to f_1(1420)\pi^-\nu_\tau)\cdot\mathcal{B}(f_1(1420)\to K^0_S K^0_S \pi^0) &= (0.24 \pm 0.05 \pm 0.06)\times 10^{-5},\\
\mathcal{B}(\tau^- \to K^*(892)^- K^0_S \pi^0\nu_\tau)\cdot\mathcal{B}(K^*(892)^-\to K^0_S \pi^-) &= (1.08 \pm 0.14 \pm 0.15)\times 10^{-5}.
\end{aligned}$$

Lepton-flavor-violating (LFV) τ decays

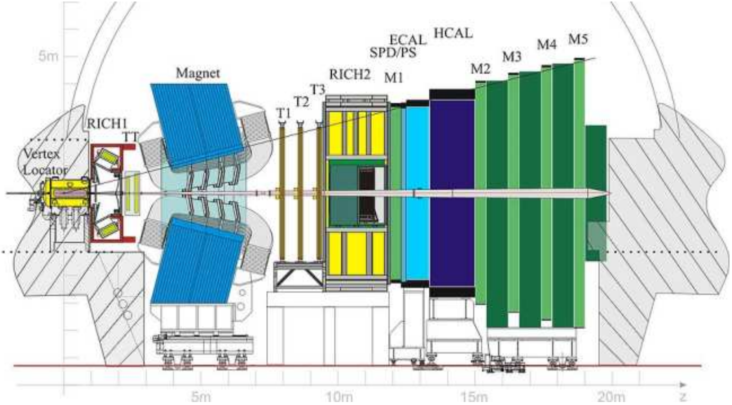


Model	$\mathcal{B}(\tau \to \mu\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
mSUGRA+seesaw	10^{-8}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-universal Z’	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-8}

- Probabililty of LFV decays of charged leptons is extremely small in the Standard Model, $\mathcal{B}(\tau \to \ell\nu) \sim \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 < 10^{-54}$
- Many models beyond the SM predict LFV decays with the branching fractions up to $\lesssim 10^{-8}$. As a result observation of LFV is a clear signature of New Physics (NP).
- τ lepton is an excellent laboratory to search for the LFV decays due to the enhanced couplings to the new particles as well as large number of LFV decay modes
- Study of the different τ LFV decay modes allows us to test various NP models.
- Recently LHCb performed results of the search for LFV $\tau^- \to \mu^-\mu^+\mu^-$ and LNV+BNV $\tau^- \to p\mu^-\mu^-,\ \bar{p}\mu^+\mu^-$ at hadronic collider (**PLB 724, 36 (2013)**).

LHCb experiment

- **One-arm forward spectrometer** (15 $\div$ 300 mrad)
- **Design luminosity:** 2×10^{32} 1/(cm^{2}s)
- **Experimental information:** 2011: 1 fb^{-1}@7 TeV, 2012: 2 fb^{-1}@8 TeV
- **Trigger:** L0(hardware): 1 MHz, HLT(software): 3-4 KHz
- μ**ID:** efficiency$\sim$97% with $\leq$3% $\pi \to \mu$ misid for $P = 2 \div 100$ GeV



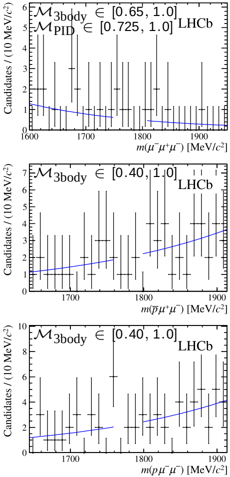
$\sigma_{\text{inclusive}}(\tau) = 80\ \mu$b @ 7 TeV (80% from $D_s^- \to \tau^- \bar{\nu}_\tau$)

LHCB is also Super-τ factory with $N(\tau) \simeq 2.4 \times 10^{11}$!

LFV $\tau^- \to \mu^-\mu^+\mu^-$, $p\mu^-\mu^-$, $\bar{p}\mu^+\mu^-$ at LHCb

Statistics of 1 fb^{-1}@7 TeV collected in 2011,
$D_s^- \to \phi(\mu^+\mu^-)\pi^-$ is used for normalization.

- $p_T^{\rm 1trk} > 0.3$ GeV/c, $p_T^{\rm 3trk} > 4$ GeV/c
- ct(SV-PV)>100 μm, $\psi(\vec{p}^{\,\rm 3trk}, \vec{R}_{SV-PV}) \sim 0^\circ$
- $M_{\mu^+\mu^-} > 0.45$ GeV/c^2 to suppress background from $D_s^- \to \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu}_\mu$
- **Blinded analysis:** $(m_\tau - 20\ \mathrm{MeV}/c^2) < \mathcal{M}_{\rm inv} < (m_\tau + 20\ \mathrm{MeV}/c^2)$ ($\pm 2\sigma_M$) region is blinded
- τ candidate is categorized using 3 likelihoods:
  - $\mathcal{M}_{\rm 3body}$: includes geometrical properties to identify displaced 3-body decays
  - $\mathcal{M}_{\rm PID}$: particle identification (RICH+ECAL+Muon)
  - $\mathcal{M}_{\rm inv}$: invariant mass of τ decay products

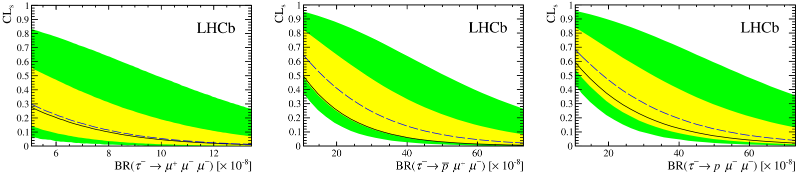


$$\mathcal{B}(\mathrm{LFV}) = \mathcal{B}(D_s^- \to \phi(\mu^+\mu^-)\pi^-)\frac{f_\tau^{D_s}}{\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)}\frac{\epsilon^{\rm det}_{\rm norm}\epsilon^{\rm trg}_{\rm norm}}{\epsilon^{\rm det}_{\rm sig}\epsilon^{\rm trg}_{\rm sig}}\frac{N_{\rm sig}}{N_{\rm norm}}$$

$f_\tau^{D_s} = 0.78 \pm 0.05$: fraction of taus from D_s^- decays

LFV $\tau^- \to \mu^-\mu^+\mu^-$, $p\mu^-\mu^-$, $\bar{p}\mu^+\mu^-$ at LHCb

	$\tau^- \to \bar{p}\mu^+\mu^-$		$\tau^- \to p\mu^-\mu^-$	
$\mathcal{M}_{3\text{body}}$	Expected	Observed	Expected	Observed
$-0.05 \div 0.20$	37.9 ± 0.8	43	41.0 ± 0.9	41
$0.20 \div 0.40$	12.6 ± 0.5	8	11.0 ± 0.5	13
$0.40 \div 0.70$	6.76 ± 0.37	6	7.64 ± 0.39	10
$0.70 \div 1.00$	0.96 ± 0.14	0	0.49 ± 0.12	0



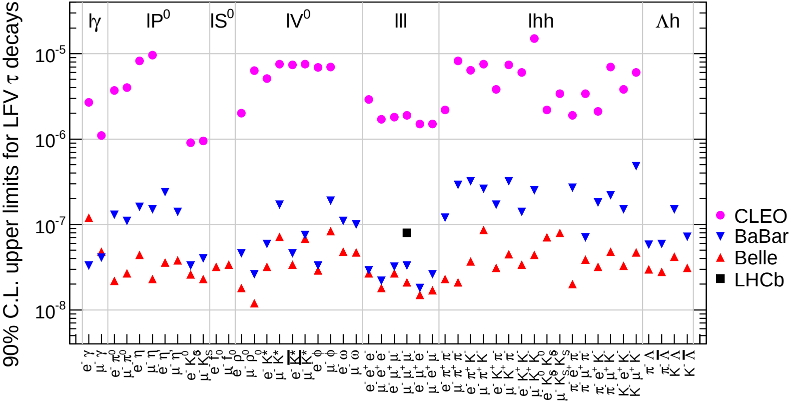
Observed limits at 90% (95%) CL:

$$\begin{aligned}
\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) &< 8.0\ (9.8) \times 10^{-8},\\
\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) &< 3.3\ (4.3) \times 10^{-7},\\
\mathcal{B}(\tau^- \to p\mu^-\mu^-) &< 4.4\ (5.7) \times 10^{-7}.
\end{aligned}$$

Decays with protons violate barion(B) and lepton(L) numbers, but $|\Delta(\mathrm{B}-\mathrm{L})| = 0$

Results on LFV decays of τ

48 different LFV modes were studied at B-factories



$$\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3 \times 10^{-7},$$
$$\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4 \times 10^{-7}.$$

First UL for BNV and LNV τ decays with protons from LHCb !

Summary

- The world largest statistics of τ leptons collected by e^+e^- B-factories (Belle and BaBar) and LHCb opens new era in the precision tests of the Standard Model and search for the effects of New Physics.
- With statistics of 711 fb^{-1} τ lifetime and upper limit on the relative lifetime difference between τ^+ and τ^- have been measured at Belle:

  $$\tau_\tau = (290.17 \pm 0.53(\text{stat}) \pm 0.33(\text{syst}))\ \text{fs.},$$
  $$|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\text{average}} < 7.0 \times 10^{-3}\ \text{at}\ 90\%\ \text{CL.}$$

  New result is almost twice more precise than the current world average value. $|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\text{average}}$ has been measured for the first time.
- Using data sample of $\int Ldt = 669\ \text{fb}^{-1}$ six τ hadronic decay modes with K_S^0 have been investigated at Belle. Branching fractions for all modes as well as for the inclusive decay $\tau^- \to K_S^0 X^- \nu_\tau$ have been measured. For the $\tau^- \to \pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$ decay $f_1(1285)\pi^- \nu_\tau$ and $K^{*-}(892) K_S^0 \nu_\tau$ mechanisms have been observed. BaBar obtained strong UL on the branching fraction of the strange hadronic decays with 3 kaons.
- With statistics of 1 fb^{-1} collected by LHCb at $\sqrt{s} = 7$ TeV searches for LFV decay $\tau^- \to \mu^-\mu^+\mu^-$ and LNV+BNV decays $\tau^- \to p\mu^-\mu^-$, $\bar{p}\mu^+\mu^-$ were carried out. Upper limits on the branching fractions of LNV+BNV decays:

  $$\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3 \times 10^{-7},$$
  $$\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4 \times 10^{-7}$$

  were measured for the first time.
- Lots of ongoing τ analyses at Belle, BaBar and LHCb, new results are expected soon.
- Broad τ physics program with ×50 statistics expected from Belle II e^+e^- Super Flavor Factory in the next decade (*today's talk about Belle II by Alan Schwartz)*.

Backup slides

CPV in hadronic τ 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
- τ 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 τ 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 $\int Ldt = 476$ fb^{-1} was analyzed

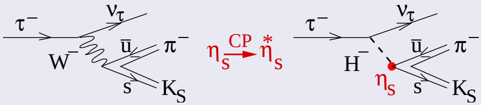
$$A_{\rm CP} = \frac{\Gamma(\tau^+\to\pi^+K^0_S(\geq 0\pi^0)\bar{\nu}_\tau) - \Gamma(\tau^-\to\pi^-K^0_S(\geq 0\pi^0)\nu_\tau)}{\Gamma(\tau^+\to\pi^+K^0_S(\geq 0\pi^0)\bar{\nu}_\tau) + \Gamma(\tau^-\to\pi^-K^0_S(\geq 0\pi^0)\nu_\tau)} = (-0.36 \pm 0.23 \pm 0.11)\%$$

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

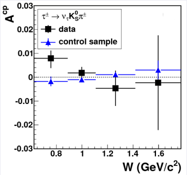
II. CPV in $\tau^- \to K^0_S\pi^-\nu_\tau$ at Belle (Phys. Rev. Lett. 107, 131801 (2011)) $\int$Ldt=699 fb^{-1}

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

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



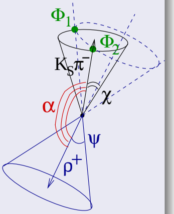
$|Im(\eta_S)| < 0.026$



Further studies of CPV in τ at e^+e^- factories

- At e^+e^- machines with unpolarized beams effect of τ spin-spin correlation in $e^+e^- \to \tau^+(\vec{\zeta}^+)\tau^-(\vec{\zeta}^-)$ reaction can be used to study CPV effects in the spin-dependent part of the decay rate.
- The idea is to study $(\tau^\mp \to h^\mp_{\mathrm{CP}}\nu\ ;\ \tau^\pm \to \rho^\pm\nu)$ events (as an example let's take $h^\mp_{\mathrm{CP}} = (K\pi)^\mp$). $\tau^\pm \to \rho^\pm\nu$ serves as spin analyzer.

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



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

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

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

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

η_{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.** Similar technique was developed to measure Michel parameters at B-factories.