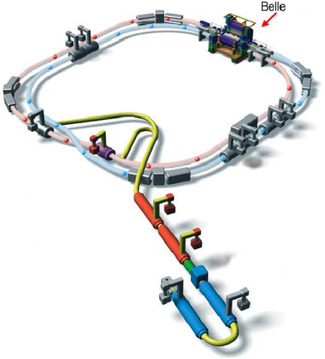
9th Belle PAC

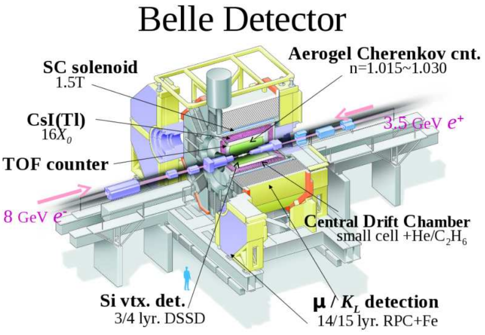
Tau and two-photon physics at Belle

D. Epifanov
The University of Tokyo
February 10th, 2015

Outline:

1. **Introduction**
2. τ **lifetime**
3. **New search for** τ **EDM**
4. **Michel parameters in** τ **decays**
5. **Hadronic decays with** K_S^0
6. **Study of** $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$
7. **Study of two-photon processes**
8. **Summary**





Process	σ, nb
$e^+e^- \to e^+e^-(\gamma)$ $15^o \leq \theta \leq 165^o$	123.5
$e^+e^- \to \mu^+\mu^-(\gamma)$	1.005
$e^+e^- \to q\overline{q}$ $(q = u, d, s, c)$	3.39
$e^+e^- \to b\overline{b}$	1.05
$e^+e^- \to e^+e^- f\overline{f}$ $(f = u, d, s, c, e, \mu, \tau)$	72.6
$e^+e^- \to \tau^+\tau^-(\gamma)$	0.919

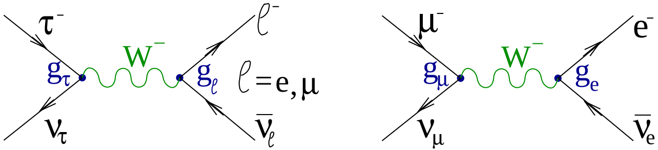
- $E_{e^-} = 8$ **GeV**, $E_{e^+} = 3.5$ **GeV**
- **Peak luminosity:** $L = 2.11 \times 10^{34}$ **cm**$^{-2}$**s**$^{-1}$
- **Integrated luminosity:** $\int Ldt \simeq 1$ **ab**$^{-1}$, $N_{\tau\tau} \simeq 10^9$
- **B-factory is also τ-factory**

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 **BES** and **KEDR** 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 tau EDM with full Belle 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, ξ_ρ, δ, $\bar{\eta}$, κ):**
  Belle: Systematics dominated measurement ($\lesssim$ 1%), study is going on; arXiv:1409.4969
- Anomalous magnetic moment of τ.
- Tau neutrino mass, search for heavy Majorana and sterile neutrinos.
  Belle: Analysis is going on.

τ-lepton lifetime, motivation

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



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

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

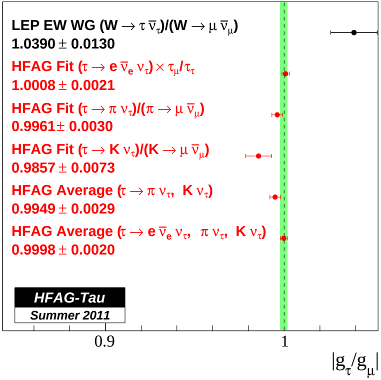
$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x, \; x = m_\ell / m_L$$

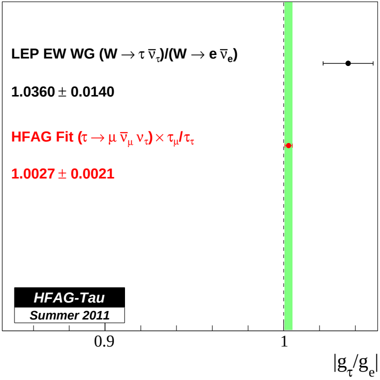
$$\mathcal{B}(\mu^- \to e^- \bar{\nu}_e \nu_\mu(\gamma)) = 1$$

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

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

τ-lepton lifetime, motivation





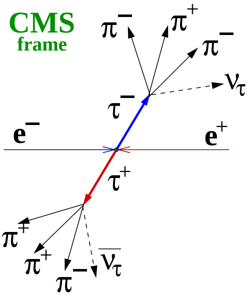
S. Schael *et al.* [ALEPH, DELPHI, L3, OPAL, LEP EWG] Phys. Rep. 532, 119 (2013)

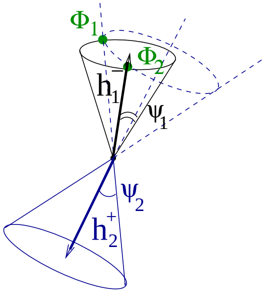
$$\frac{2\mathcal{B}(W \to \tau\nu_\tau)}{\mathcal{B}(W \to \mu\nu_\mu) + \mathcal{B}(W \to e\nu_e)} = 1.066 \pm 0.025$$

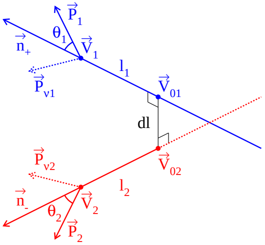
2.6σ **deviation from the Standard Model**

τ-lepton lifetime, method

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







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

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

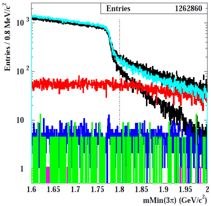
- τ momentum direction is determined with two-fold ambiguity in CMS, for the analysis we use the average axis.
- Asymmetric-energy layout of experiment allows us to determine $\tau^+\tau^-$ production point in LAB independently from the position of beam IP.
- Possibility to test CPT conservation measuring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

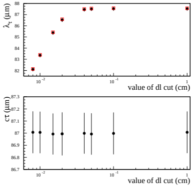
τ-lepton lifetime, selections

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_S^0, Λ, π^0 candidates. Number of additional photons $N_\gamma < 6$ with $E_\gamma^{\rm TOT} < 0.7$ GeV.
- $P_\perp(6\pi) > 0.5$ GeV/c, 4 GeV/c^2 $< M_{\rm inv}(6\pi) < 10.25$ GeV/c^2.
- Pseudomass $\sqrt{M_h^2 + 2(E_{\rm beam} - E_h)(E_h - P_h)} < 1.8$ 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 $\sim$2% background contamination, the main background comes from $e^+e^- \to q\bar{q}$ ($q =$u, d, s).

τ-lepton lifetime, fit of decay length

Decay length PDF

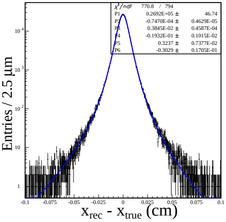
$$\mathcal{P}(x) = \mathcal{N} \int e^{-x'/\lambda_\tau} R(x - x'; \vec{P}) dx' + \mathcal{N}_{uds} R(x; \vec{P}) + \mathcal{P}_{cb}(x),$$

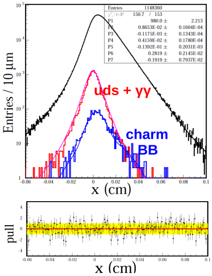
$$R(x; \vec{P}) = (1 - 2.5x) \cdot \exp\left(-\frac{(x - P_1)^2}{2\sigma^2}\right),$$

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

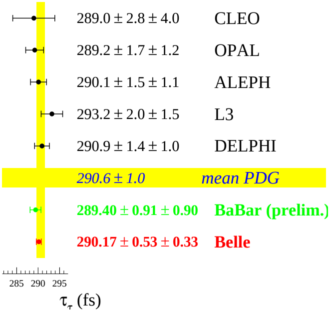
- Free parameters of the fit: λ_τ, $\mathcal{N}$, $\vec{P} = (P_1, \ldots, P_5)$
- λ_τ - estimator of $c\tau_\tau$, $c\tau_\tau = \lambda_\tau + \Delta_{\rm corr}$, $\Delta_{\rm corr}$ is determined from MC;
- $R(x; \vec{P})$ - detector resolution function;
- $\mathcal{N}_{uds}$ - contribution of background 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)

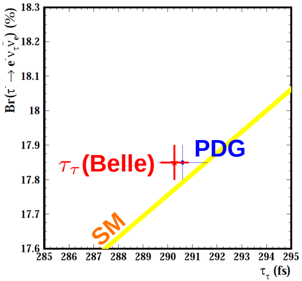
From the fit of experimental data
$\lambda_\tau = 86.53 \pm 0.16$ μm, applying correction
$\Delta_{\rm corr} = 0.46$ μm we got: $c\tau_\tau = 86.99 \pm 0.16$ μm





τ-lepton lifetime, 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**

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

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

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

Lepton universality

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

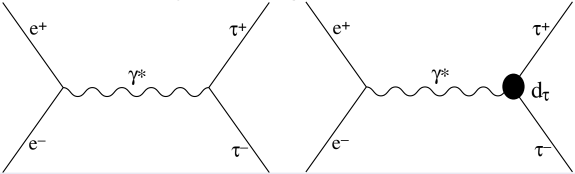
$$\mathbf{g_\tau/g_e = 1.0031 \pm 0.0016}\ (\text{new Belle } \tau_\tau)$$

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

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

Electric dipole moment of τ, introduction

Electric dipole moment (EDM) of τ is strongly suppressed in the Standard Model ($\mathcal{O}(10^{-37})$ e·cm), EDM$\neq 0$ indicates the nonconservation of **T**(**CP**) and **P** symmetries. EDM provides powerful tool to search for New Physics in lepton sector.



$$\mathcal{L} = \bar{\tau}((i\partial_\mu - eA_\mu)\gamma^\mu - m)\tau - id_\tau \bar{\tau}\sigma^{\mu\nu}\gamma^5\tau\partial_\mu A_\nu$$

$$\mathcal{M}^2_{tot} = \mathcal{M}^2_{SM} + Re(d_\tau)\mathcal{M}^2_{Re} + Im(d_\tau)\mathcal{M}^2_{Im} + |d_\tau|^2\mathcal{M}^2_{d^2}$$

$$\frac{d\Gamma(\tau^\mp \to h^\mp\nu)}{d\mathcal{PS}} = F(1 \pm \vec{\zeta}_{\tau^\mp}\vec{H}_{h^\mp}),\ \vec{H}_{\pi^\mp} = \vec{p}_{\pi^\mp}/|\vec{p}_{\pi^\mp}|$$

$\vec{\zeta}_{\tau^\mp}$ - unitary $\tau^\mp$ polarization vector; $\vec{H}_{h^\mp}$ - $h^\mp$ polarimeter vector.

$$\mathcal{M}^2_{Re} \sim (\vec{H}_{h_1^+}\times\vec{H}_{h_2^-})\vec{p}_e,\ (\vec{H}_{h_1^+}\times\vec{H}_{h_2^-})\vec{p}_\tau\ : \mathrm{CP-odd,\ T-odd\ (CPT-cons.)}$$

$$\mathcal{M}^2_{Im} \sim (\vec{H}_{h_1^+}-\vec{H}_{h_2^-})\vec{p}_e,\ (\vec{H}_{h_1^+}-\vec{H}_{h_2^-})\vec{p}_\tau\ : \mathrm{CP-odd,\ T-even\ (CPT-viol.)}$$

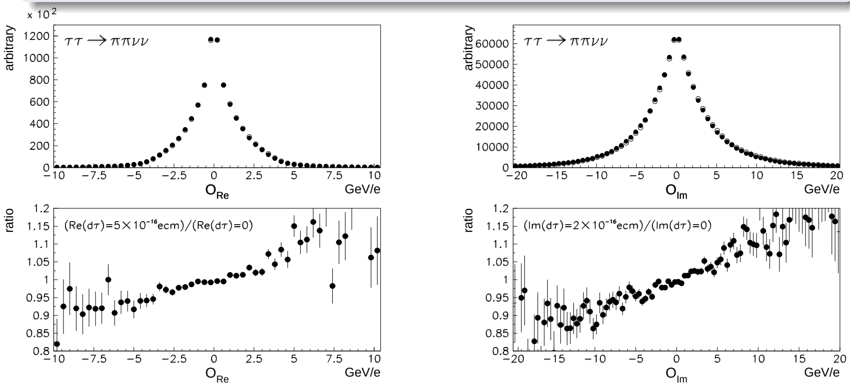
Tau EDM, method

Method of optimal variable is used to measure $\mathrm{Re}(d_\tau)$ and $\mathrm{Im}(d_\tau)$.

$$\mathcal{O}_{\mathrm{Re}} = \frac{\mathcal{M}^2_{\mathrm{Re}}}{\mathcal{M}^2_{\mathrm{SM}}},\ \mathcal{O}_{\mathrm{Im}} = \frac{\mathcal{M}^2_{\mathrm{Im}}}{\mathcal{M}^2_{\mathrm{SM}}},\ \langle \mathcal{O}_{\mathrm{Re,Im}} \rangle \sim \int \mathcal{O}_{\mathrm{Re,Im}} \mathcal{M}^2_{\mathrm{tot}} d\mathcal{PS}$$

$$\langle \mathcal{O}_{\mathrm{Re}} \rangle = \mathbf{a}_{\mathrm{Re}} \mathrm{Re}(d_\tau) + \mathbf{b}_{\mathrm{Re}},\ \langle \mathcal{O}_{\mathrm{Im}} \rangle = \mathbf{a}_{\mathrm{Im}} \mathrm{Im}(d_\tau) + \mathbf{b}_{\mathrm{Im}}$$

$$\mathbf{a}_{\mathrm{Re,Im}} = \langle \mathcal{O}^2_{\mathrm{Re,Im}} \rangle = \int \frac{(\mathcal{M}^2_{\mathrm{Re,Im}})^2}{\mathcal{M}^2_{\mathrm{SM}}} d\mathcal{PS},\ \mathbf{b}_{\mathrm{Re,Im}} = \int \mathcal{M}^2_{\mathrm{Re,Im}} d\mathcal{PS}$$

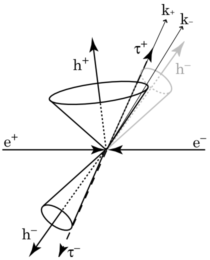


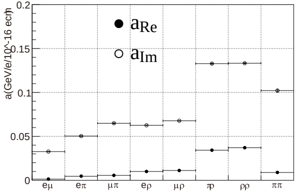
Tau EDM, data/selections

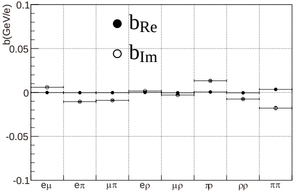
Statistics with $\int Ldt = 825$ fb^{-1} ($N_{\tau\tau} = 758 \times 10^6$) is used.
In total about 35M events are selected with the purity of 88%.

Select 8 configurations: $(e\nu\nu;\ \mu\nu\nu)$, $(e\nu\nu;\ \pi\nu)$, $(e\nu\nu;\ \rho\nu)$, $(\mu\nu\nu;\ \pi\nu)$, $(\mu\nu\nu;\ \rho\nu)$, $(\pi\nu;\ \pi\nu)$, $(\pi\nu;\ \rho\nu)$, $(\rho\nu;\ \rho\nu)$.
In the calculation of $\mathcal{O}_{\rm Re,Im}$ the average allowed τ direction is used. Coefficients $\mathbf{a}_{\rm Re,Im}$ and $\mathbf{b}_{\rm Re,Im}$ are determined from MC.

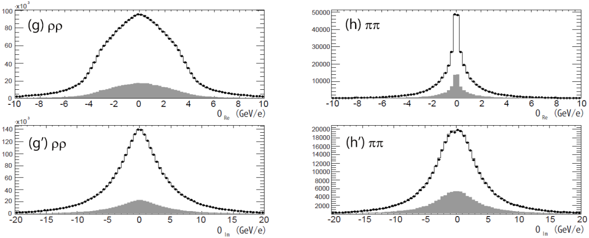
mode	yield	purity(%)	background (%)
$e\mu$	6434k	95.8	$2\gamma \to \mu\mu(2.5)$, $\tau\tau \to e\pi(1.3)$
$e\pi$	2645k	85.7	$\tau\tau \to e\rho(6.5)$ $e\mu(5.1)$ $eK^*(1.3)$
$e\rho$	7219k	91.7	$\tau\tau \to e\pi 2\pi^0(4.6)$ $eK^*(1.7)$
$\mu\pi$	2504k	80.5	$\tau\tau \to \mu\rho(6.4)$ $\mu\mu(4.9)$ $\mu K^*(1.3)$, $2\gamma \to \mu\mu(3.1)$
$\mu\rho$	6203k	91.0	$\tau\tau \to \mu\pi 2\pi^0(4.3)$ $\mu K^*(1.6)$ $\pi\rho(1.1)$
$\pi\pi$	921k	71.9	$\tau\tau \to \pi\rho(11.3)$ $\pi\mu(8.8)$ $\pi K^*(2.5)$
$\pi\rho$	2656k	77.0	$\tau\tau \to \rho\rho(6.7)$ $\pi\pi 2\pi^0(3.9)$ $\mu\rho(5.1)$ $\rho K^*(1.4)$ $\pi K^*(1.4)$
$\rho\rho$	6554k	82.4	$\tau\tau \to \rho\pi 2\pi^0(9.4)$ $\rho K^*(3.1)$







Tau EDM, preliminary result



$\mathrm{Re}(d_\tau)$	$e\mu$	$e\pi$	$\mu\pi$	$e\rho$	$\mu\rho$	$\pi\rho$	$\rho\rho$	$\pi\pi$
Mismatch of distribution	0.30	0.47	0.35	0.08	0.17	0.08	0.08	0.34
Charge asymmetry	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Background variation	0.16	0.03	0.16	0.04	0.02	0.02	0.02	0.33
Momentum reconstruction	0.01	0.06	0.05	0.00	0.02	0.02	0.01	0.14
Detector alignment	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.03
Radiative effects	0.07	0.05	0.05	0.02	0.02	0.00	0.00	0.09
Total	0.35	0.47	0.39	0.09	0.17	0.08	0.08	0.50

$\mathrm{Im}(d_\tau)$	$e\mu$	$e\pi$	$\mu\pi$	$e\rho$	$\mu\rho$	$\pi\rho$	$\rho\rho$	$\pi\pi$
Mismatch of distribution	0.09	0.09	0.05	0.05	0.07	0.04	0.04	0.12
Charge asymmetry	0.02	0.19	0.23	0.01	0.01	0.11	0.00	0.00
Background variation	0.14	0.01	0.07	0.03	0.01	0.01	0.01	0.01
Momentum reconstruction	0.02	0.05	0.04	0.00	0.01	0.01	0.00	0.01
Detector alignment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radiative effects	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Total	0.17	0.22	0.24	0.06	0.07	0.11	0.04	0.12

Sensitivity: $\Delta\mathrm{Re}(d_\tau) = 0.33 \times 10^{-17}\ e\cdot\mathrm{cm}$, $\Delta\mathrm{Im}(d_\tau) = 0.30 \times 10^{-17}\ e\cdot\mathrm{cm}$

Compare with previous Belle result: PLB 551, 16 (2003) ($\int Ldt = 29.5\ \mathrm{fb}^{-1}$)

$\mathrm{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}\ e\cdot\mathrm{cm}$, $\mathrm{Im}(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17}\ e\cdot\mathrm{cm}$

Michel parameters in τ decays, motivation

In the SM charged weak interaction is described by the exchange of $W^\pm$ with a pure vector coupling to only left-handed fermions ("V-A" Lorentz structure). Deviations from "V-A" indicate New Physics. $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ ($\ell = e, \mu$) decays provide clean laboratory to probe electroweak couplings.

The most general, Lorentz invariant four-lepton interaction matrix element:

$$\mathcal{M} = \frac{4G}{\sqrt{2}} \sum_{\substack{N=S,V,T \\ i,j=L,R}} g_{ij}^N \left[\bar{u}_i(l^-)\Gamma^N v_n(\bar{\nu}_l)\right] \left[\bar{u}_m(\nu_\tau)\Gamma_N u_j(\tau^-)\right],$$

$$\Gamma^S = 1,\ \Gamma^V = \gamma^\mu,\ \Gamma^T = \frac{i}{2\sqrt{2}}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$$

Ten couplings g_{ij}^N, in the SM the only non-zero constant is $g_{LL}^V = 1$

Four bilinear combinations of g_{ij}^N, which are called as Michel parameters (MP): ρ, η, ξ and δ appear in the energy spectrum of the outgoing lepton:

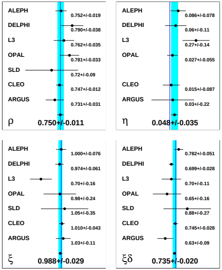
$$\frac{d\Gamma(\tau^\mp)}{d\Omega dx} = \frac{4G_F^2 M_\tau E_{\max}^4}{(2\pi)^4}\sqrt{x^2 - x_0^2}\Bigg(x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

$$\mp \frac{1}{3}P_\tau cos\theta_\ell \xi \sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left(4x - 4 + \sqrt{1 - x_0^2}\right)\right]\Bigg),\ x = \frac{E_\ell}{E_{\max}},\ x_0 = \frac{m_\ell}{E_{\max}}$$

In the SM: $\rho = \frac{3}{4}$, $\eta = 0$, $\xi = 1$, $\delta = \frac{3}{4}$

Status of Michel parameters in τ decays

Michel par.	Measured value	Experiment	SM value
ρ (e or μ)	$0.747 \pm 0.010 \pm 0.006$ 1.2%	CLEO-97	3/4
η (e or μ)	$0.012 \pm 0.026 \pm 0.004$ 2.6%	ALEPH-01	0
ξ (e or μ)	$1.007 \pm 0.040 \pm 0.015$ 4.3%	CLEO-97	1
$\xi\delta$ (e or μ)	$0.745 \pm 0.026 \pm 0.009$ 2.8%	CLEO-97	3/4
ξ_h (all hadr.)	$0.992 \pm 0.007 \pm 0.008$ 1.1%	ALEPH-01	1

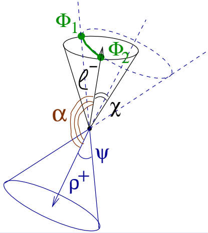


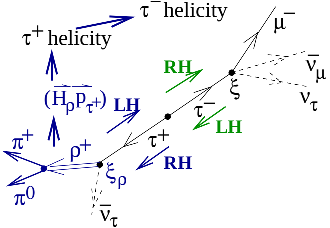
With $\times$300 Belle statistics we can improve MP uncertainties by one order of magnitude
In BSM models the couplings to τ are expected to be enhanced in comparison with μ.
Also contribution from New Physics in τ decays can be amplified by $(\frac{m_\tau}{m_\mu})^n$.

- **Type II 2HDM:** $\eta_\mu(\tau) = \frac{m_\mu M_\tau}{2}\left(\frac{\tan^2\beta}{M^2_{H^\pm}}\right)^2$; $\frac{\eta_\mu(\tau)}{\eta_e(\mu)} = \frac{M_\tau}{m_e} \approx 3500$
- **Tensor interaction:** $\mathcal{L} = \frac{g}{2\sqrt{2}} W^\mu \left\{ \bar{\nu}\gamma_\mu(1-\gamma^5)\tau + \frac{\kappa^W_\tau}{2m_\tau}\partial^\nu \left(\bar{\nu}\sigma_{\mu\ nu}(1-\gamma^5)\tau\right)\right\}$,
  $-0.096 < \kappa^W_\tau < 0.037$: DELPHI Abreu EPJ C16 (2000) 229.
- **Unparticles:** Moyotl PRD 84 (2011) 073010, Choudhury PLB 658 (2008) 148.
- **Lorentz and CPTV:** Hollenberg PLB **701** (2011) 89
- **Heavy Majorana neutrino:** M. Doi *et al.*, Prog. Theor. Phys. **118** (2007) 1069.

Michel parameters in τ decays, method

Effect of τ spin-spin correlation is used to measure ξ and δ MP.
Events of $(\tau^{\mp} \to \ell^{\mp}\nu\nu;\ \tau^{\pm} \to \rho^{\pm}\nu)$ topology are used to measure: ρ, η, $\xi_\rho\xi$ and $\xi_\rho\xi\delta$, while $(\tau^{\mp} \to \rho^{\mp}\nu;\ \tau^{\pm} \to \rho^{\pm}\nu)$ events are used to extract ξ_ρ^2.





$$\frac{d\sigma(\ell^{\mp},\rho^{\pm})}{dE^*_\ell\, d\Omega^*_\ell\, d\Omega^*_\rho\, dm^2_{\pi\pi}\, d\tilde{\Omega}_\pi\, d\Omega_\tau} = A_0 + \rho A_1 + \eta A_2 + \xi_\rho\xi A_3 + \xi_\rho\xi\delta A_4 = \sum_{i=0}^{4} A_i \Theta_i$$

$$\mathcal{F}(\vec{z}) = \frac{d\sigma(\ell^{\mp},\rho^{\pm})}{dp_\ell\, d\Omega_\ell\, dp_\rho\, d\Omega_\rho\, dm^2_{\pi\pi}\, d\tilde{\Omega}_\pi} = \int_{\Phi_1}^{\Phi_2} \frac{d\sigma(\ell^{\mp},\rho^{\pm})}{dE^*_\ell\, d\Omega^*_\ell\, d\Omega^*_\rho\, dm^2_{\pi\pi}\, d\tilde{\Omega}_\pi\, d\Omega_\tau} \left| \frac{\partial(E^*_\ell,\Omega^*_\ell,\Omega^*_\rho,\Omega_\tau)}{\partial(p_\ell,\Omega_\ell,p_\rho,\Omega_\rho,\Phi_\tau)} \right| d\Phi_\tau$$

$$L = \prod_{k=1}^{N} \mathcal{P}^{(k)},\ \mathcal{P}^{(k)} = \mathcal{F}(\vec{z}^{(k)})/\mathcal{N}(\vec{\Theta}),\ \mathcal{N}(\vec{\Theta}) = \int \mathcal{F}(\vec{z})d\vec{z},\ \vec{\Theta} = (1, \rho, \eta, \xi_\rho\xi_\ell, \xi_\rho\xi_\ell\delta_\ell)$$

MP are extracted in the unbinned maximum likelihood fit of $(\ell,\ \rho)$ events in the 9D phase space $\vec{z} = (p_\ell,\ \cos\theta_\ell,\ \phi_\ell,\ p_\rho,\ \cos\theta_\rho,\ \phi_\rho,\ m^2_{\pi\pi},\ \cos\tilde{\theta}_\pi,\ \tilde{\phi}_\pi)$ in CMS.

Physical corrections and detector effects are also taken into account.

Michel parameters in τ decays, background

EXP data sample with $\int$Ldt= 485 fb^{-1} (446 $\times 10^6$ $\tau^+\tau^-$) with about 5.5M events of all 4 configurations were selected. Signal detection efficiency $\bar{\varepsilon} \simeq 12\%$.

The main background comes from $\ell - \pi\pi^0\pi^0$ ($\simeq$10%) and $\pi - \pi\pi^0(\pi \to \mu)$ ($\simeq$1.5%) events, they are included in PDF analytically. The remaining background ($\simeq$2.0%) is taken into account using MC-based approach. Background from the non-$\tau\tau$ events is $\lesssim 0.1\%$.

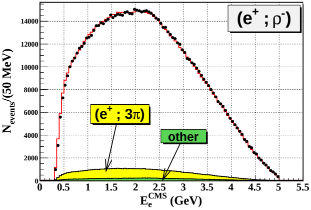
Likelihood per event

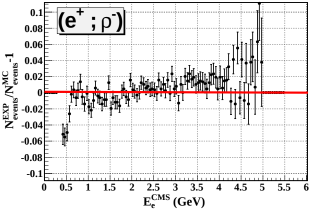
$$\mathcal{P}(x) = \frac{\varepsilon(x)}{\bar{\varepsilon}}\left((1-\sum_i \lambda_i)\frac{S(x)}{\int \frac{\varepsilon(x)}{\bar{\varepsilon}}S(x)dx} + \lambda_{3\pi}\frac{\tilde{B}_{3\pi}(x)}{\int \frac{\varepsilon(x)}{\bar{\varepsilon}}\tilde{B}_{3\pi}(x)dx} + \lambda_{\pi}\frac{\tilde{B}_{\pi}(x)}{\int \frac{\varepsilon(x)}{\bar{\varepsilon}}\tilde{B}_{\pi}(x)dx} + \lambda_{other}\frac{B^{MC}_{other}(x)}{\int \frac{\varepsilon(x)}{\bar{\varepsilon}}B^{MC}_{other}(x)dx}\right)$$

$$\tilde{B}_{3\pi}(x) = \int (1-\varepsilon_{\pi^0}(y))\varepsilon_{add}(y)B_{3\pi}(x,y)dy,\ \tilde{B}_{\pi}(x) = \frac{\varepsilon_{\pi}(x)}{\varepsilon(x)}B_{\pi}(x),\ \frac{\varepsilon_{\pi}(x)}{\varepsilon(x)} = \frac{\varepsilon^{\mu ID}_{\pi\to\mu}(x)}{\varepsilon^{\mu ID}_{\mu\to\mu}(x)}$$

- $x = (p_\ell,\ \Omega_\ell,\ p_\rho,\ \Omega_\rho,\ m^2_{\pi\pi},\ \tilde{\Omega}_\pi)$; $y = (p_{\pi^0},\ \Omega_{\pi^0})$;
- $S(x)$ - density of signal $(\ell^\mp,\ \pi^\pm\pi^0)$ events;
- $B_{3\pi}(x,y)$ - density of background $(\ell^\mp,\ \pi^\pm 2\pi^0)$ events;
- $B_\pi(x)$ - density of background $(\pi^\mp,\ \pi^\pm\pi^0)$ events;
- $B^{MC}_{other}(x)$ - MC density of the remaining background;
- $\varepsilon(x)$ - detection efficiency for signal events;
- $\varepsilon_{\pi^0}(y)$ - π^0 detection efficiency;
- $\varepsilon_{add}(y)$ - additional efficiency for $(\ell^\mp,\ \pi^\pm 2\pi^0)$ events;
- $\varepsilon_\pi(x)$ - detection efficiency for $(\pi^\mp,\ \pi^\pm\pi^0)$ events;

We confirmed that with Belle data the statistical accuracy of Michel parameters is by one order of magnitude better than in the previous best measurements (CLEO, ALEPH).





Source	$\sigma(\rho)$, %	$\sigma(\eta)$, %	$\sigma(\xi_\rho\xi)$, %	$\sigma(\xi_\rho\xi\delta)$, %
Physical corrections				
ISR+$\mathcal{O}(\alpha^3)$	0.10	0.30	0.20	0.15
$\tau \to \ell\nu\nu\gamma$	0.03	0.10	0.09	0.08
$\tau \to \rho\nu\gamma$	0.06	0.16	0.11	0.02
Apparatus corrections				
Res. $\oplus$ brems.	0.10	0.33	0.11	0.19
$\sigma(E_{\rm beam})$	0.07	0.25	0.03	0.15
Normalisation				
$\Delta\mathcal{N}$	0.21	0.60	0.38	0.26
Total	**0.27**	**0.81**	**0.47**	**0.40**

A few percent systematic effect arising from the inaccurate description of the $\ell - 3\pi$ background is under investigation.
The dominant systematic uncertainties come from the various EXP/MC efficiency corrections related to: **trigger, track/photon/π^0 reconstruction, $\pi^\mp$ and $\ell^\mp$ identification**.

Hadronic τ decays, motivation

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)

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

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_{us}:

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

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

Study of $\tau^- \to K_S^0 X^- \nu_\tau$ decays, selections

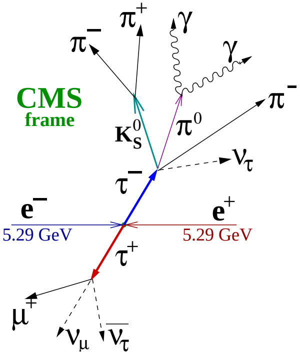
S. Ryu *et al.* [Belle Collaboration], Phys. Rev. D **89**, 072009 (2014)

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:

$$\pi^- K_S^0 \nu_\tau \qquad K^- K_S^0 \nu_\tau \qquad \pi^- K_S^0 K_S^0 \nu_\tau$$
$$\pi^- K_S^0 \pi^0 \nu_\tau \qquad K^- K_S^0 \pi^0 \nu_\tau \qquad \pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$$

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



Study of $\tau^- \to K_S^0 X^- \nu_\tau$ decays, branchings

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:

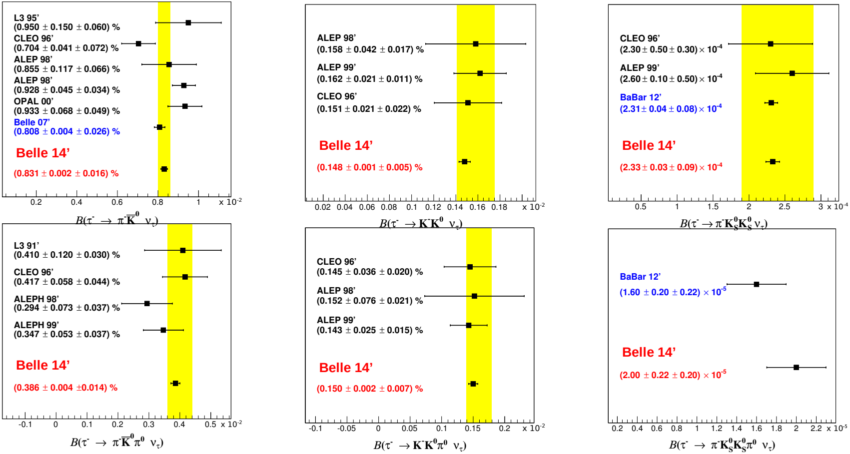
$$\mathcal{B}_i = \frac{N_i^{\rm sig}}{N_{e\text{-}\mu}^{\rm sig}} \frac{\mathcal{B}_e \mathcal{B}_\mu}{\mathcal{B}_e + \mathcal{B}_\mu}$$

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:

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

Study of $\tau^- \to K_S^0 X^- \nu_\tau$ decays, result

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



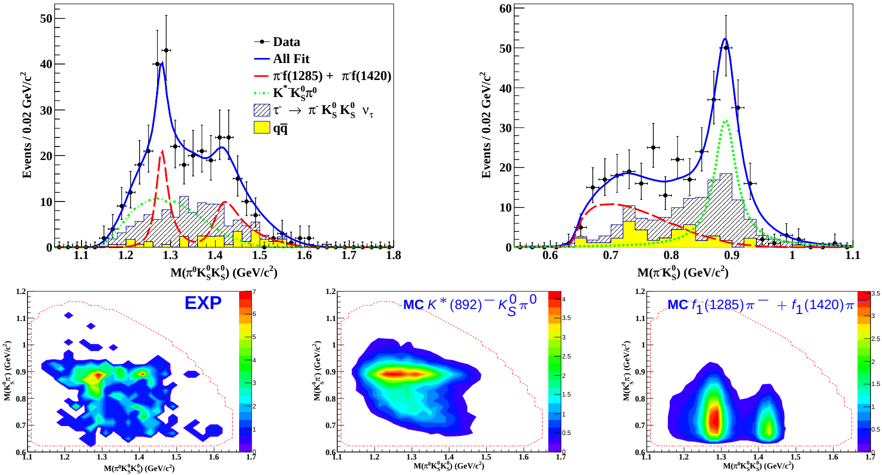
Yellow bands show the world averages and their uncertainties from PDG:

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

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

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

$f_1(1285)\pi^-(34\pm5)\% \oplus f_1(1420)\pi^-(12\pm3)\% \oplus K^*(892)^- K_S^0\pi^0(54\pm6)\%$



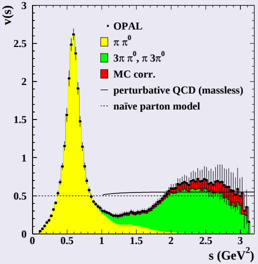
Simultaneous fit of $M_{\rm INV}(\pi^0 K_S^0 K_S^0)$($f_1(1285)$ and $f_1(1420)$) and $M_{\rm INV}(\pi^- K_S^0)$($K^*(892)^-$) distributions.

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

Study of $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$, motivation

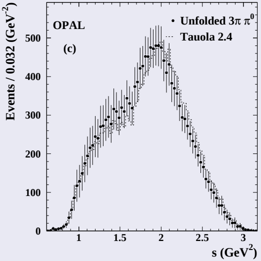
Motivation:

- Notable part of the **vector spectral function (v(s))** needed for the precision determination of $\alpha_s(s)$
- Test of the CVC theorem for the 4π hadronic system:
  $v(\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau) = \frac{s}{4\pi^2\alpha^2} \times$
  $\times \left(\frac{1}{2}\sigma(e^+e^- \to 2\pi^+\pi^-) + \sigma(e^+e^- \to \pi^+\pi^- 2\pi^0) \right)$
- Contribution of the 2nd-class current in the decay $\tau^- \to \omega\pi^-\nu_\tau$ $(\omega \to \pi^+\pi^-\pi^0)$
- **Improvement from B factories is strongly expected**



$$v(s) = \frac{m_\tau^2}{6S_{\rm EW}|V_{\rm ud}|^2(1-s/m_\tau^2)^2(1+2s/m_\tau^2)} \times$$
$$\times \frac{\mathcal{B}(\tau^- \to V^-\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)} \frac{1}{N}\frac{dN}{ds}$$

- $s = M_V^2$
- $S_{\rm EW}$ - electroweak radiative correction
- **Both, branching ratio $\mathcal{B}(\tau^- \to V^-\nu_\tau)$ and mass spectrum $\frac{1}{N}\frac{dN}{ds}$ should be measured precisely**

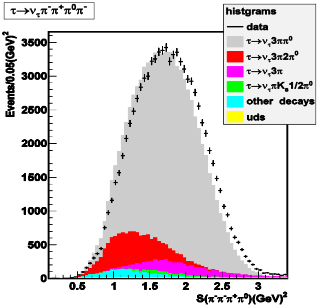


Study of $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$, method

Data sample of $\int Ldt = 670$ fb^{-1} ($N_{\tau\tau} = 616 \times 10^6$) is analyzed

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

- Selection criteria on the missing mass and polar angle of the missing momentum to suppress background from Bhabha, $\mu\mu$, two-photon processes, $\sum_{\rm ntrk=1}^{4} Q_i = 0$.
- Event is separated into two hemispheres in CMS: Thrust>0.9, $35^\circ < \theta^{\rm CMS}_{\rm thrust} < 145^\circ$.
- Tag side: 1 track identified as e or μ.
- Signal side: 3 tracks identified as pions, and π^0 candidate with $-6 < \frac{m_{\gamma\gamma} - m_{\pi^0}}{\sigma_{\gamma\gamma}} < 5$.
- $E^{\rm LAB}_{\gamma extra} < 0.2$ GeV



$(\tau^\mp \to e^\mp\nu\nu; \tau^\pm \to \mu^\pm\nu\nu)$ **sample is used for the normalization:**

$$\mathcal{B}(\tau^- \to (4\pi)^-\nu_\tau) = \frac{N_{\ell-4\pi}(1-b_{\ell-4\pi})}{\varepsilon_{\ell-4\pi}} \times \frac{\varepsilon_{e-\mu}}{N_{e-\mu}(1-b_{e-\mu})} \times \frac{\mathcal{B}_e\mathcal{B}_\mu}{\mathcal{B}_e+\mathcal{B}_\mu}$$

- Detection efficiencies: $\varepsilon_{\ell-4\pi} \simeq 8\%$, $\varepsilon_{e-\mu} \simeq 18\%$
- Background admixtures: $b_{\ell-4\pi} \simeq 12\%$ (primarily from the other τ decays), $b_{e-\mu} \simeq 4\%$
- $\mathcal{B}_e = (17.83 \pm 0.04)\%$, $\mathcal{B}_\mu = (17.41 \pm 0.04)\%$

Systematic shift between measured 4π mass distribution and TAUOLA (VEPP-2M, $e^+e^- \to 4\pi$) predicted spectrum is notable.

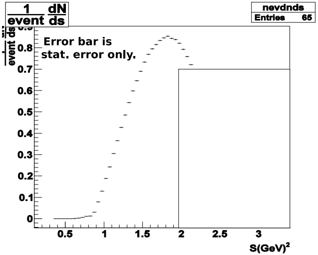
Study of $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$, preliminary result

Using part of the full data sample (25 fb^{-1}) **preliminary result** on the branching fraction was obtained:

$$\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau)_{\text{ex. K}^0_\text{S}} = (4.38 \pm 0.02_{\text{stat.}} \pm 0.12_{\text{syst.}})\%$$

Error source	$\Delta\mathcal{B}/\mathcal{B}$ (%)
Tracking efficiency	0.7
Particle identification	1.5
π^0 reconstruction	1.5
Background	
τ feed-down background	0.3
$q\bar{q}$ contribution	0.3
Normalization	
background of $e - \mu$ events	0.5
$\Delta\mathcal{B}_e$, $\Delta\mathcal{B}_\mu$	0.1
γ veto	1.2
Trigger efficiency	0.8
Hadron decay model	0.7
Total	2.8

$\mathcal{B}(\tau \to 4\pi\nu)$ **(%)**	**EXP**
$4.60 \pm 0.06 \pm 0.06$	ALEPH
$4.19 \pm 0.10 \pm 0.21$	CLEO



Singular-value decomposition (SVD) method was used to get unfolded 4π mass spectrum. It is crucial to subtract background from the $\tau^- \to \pi^-\pi^+\pi^-\pi^0\pi^0\nu_\tau$ decay correctly, the analysis is going on.

In contrary to OPAL result, no shoulder is seen around $s = 1.5$ GeV$^2/c^4$.

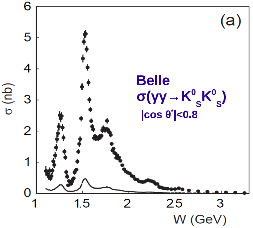
Two-photon physics at Belle

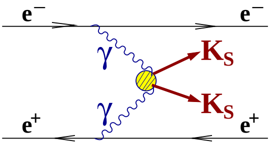
Cross section of $\gamma\gamma \to$ final

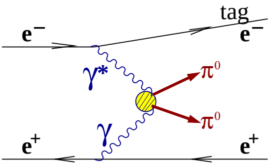
$$\frac{d\sigma}{d|\cos\theta^*|} = \frac{\Delta N}{\Delta W \Delta|\cos\theta^*| \int L dt \frac{dL_{\gamma\gamma}}{dW} \varepsilon(W, |\cos\theta^*|)}$$

- $W = M_{\gamma\gamma}$; θ^* - scattering angle in $\gamma\gamma$ system
- $\int L dt \frac{dL_{\gamma\gamma}}{dW}$ - effective differential $\gamma\gamma$ luminosity
- $\varepsilon(W, |\cos\theta^*|)$ - detection efficiency

- **No-tag method:** $e^+e^- \to e^+e^- K^0_S K^0_S$ PTEP 123C01 (2013)
- **Single-tag method:** $e^+e^- \to e^+e^- \pi^0\pi^0$ on-going analysis







Results on $e^+e^- \to e^+e^-\pi^0\pi^0$ can be used in a model-independent evaluation of the hadronic light-by-light contribution to the anomalous magnetic moment of muon: **G. Colangelo *et al.*, JHEP 1409 (2014) 091; Phys. Lett. B 738 (2014) 6.**

Summary

- **The world largest statistics of τ leptons collected by Belle 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:

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

  New result is almost twice more precise than the previous world average value. $|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\mathrm{average}}$ has been measured for the first time.
- Analyzing data sample of 825 fb^{-1} τ EDM is studied exploiting optimal variable method. Reduced statistical and systematic uncertainties result in the improved sensitivity:

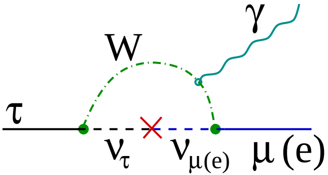
  $$\Delta\mathrm{Re}(d_\tau) = 0.33 \times 10^{-17}\ e\cdot\mathrm{cm};\ \ \Delta\mathrm{Im}(d_\tau) = 0.30 \times 10^{-17}\ e\cdot\mathrm{cm}$$
- Study of Michel parameters in leptonic τ decays is done at Belle. The work on the reduction of the systematic uncertainties is going on.
- Using data sample of $\int Ldt = 669$ 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.
- Preliminary result on the branching fraction and spectral function of the $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ decay was obtained:

  $$\mathcal{B}(\tau^- \to (4\pi)^-\nu_\tau)_{\mathrm{ex.}\ K_S^0} = (4.38 \pm 0.02_{\mathrm{stat.}} \pm 0.12_{\mathrm{syst.}})\%$$

  The unfolded spectral function is under investigation.
- Study of $\pi^0\pi^0$ production in single-tag two-photon collisions is going on.
- **Broad τ and two-photon physics program with $\times 50$ statistics expected from Belle II e^+e^- Super Flavor Factory in the next decade.**

Backup slides

Lepton-flavor-violating (LFV) τ decays

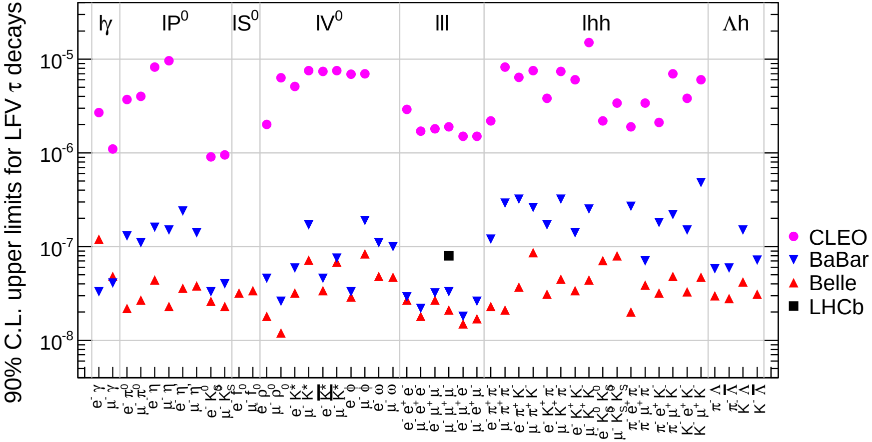


Model	$\mathcal{B}(\tau \to \mu\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
mSUGRA+seesaw	10^{-8}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-8}

- 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.

Results on LFV decays of τ

48 different LFV modes were studied at B-factories



At Belle II UL will be improved at least by 1 order of magnitude.

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

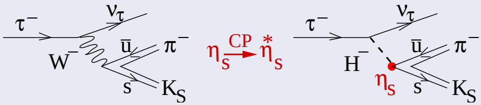
$$A_{\rm CP} = \frac{\Gamma(\tau^+\to\pi^+K^0_S(\geq 0\pi^0)\bar{\nu}_\tau) - \Gamma(\tau^-\to\pi^-K^0_S(\geq 0\pi^0)\nu_\tau)}{\Gamma(\tau^+\to\pi^+K^0_S(\geq 0\pi^0)\bar{\nu}_\tau) + \Gamma(\tau^-\to\pi^-K^0_S(\geq 0\pi^0)\nu_\tau)} = (-0.36 \pm 0.23 \pm 0.11)\%$$

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

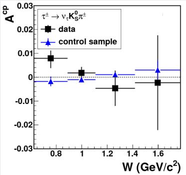
II. CPV in $\tau^- \to K^0_S \pi^- \nu_\tau$ at Belle (Phys. Rev. Lett. 107, 131801 (2011)) $\int$Ldt=699 fb^{-1}

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

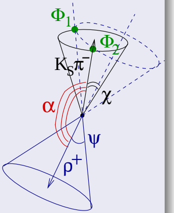
- At e^+e^- machines with unpolarized beams effect of τ spin-spin correlation in $e^+e^- \to \tau^+(\vec{\zeta}^+)\tau^-(\vec{\zeta}^-)$ reaction can be used to study CPV effects in the spin-dependent part of the decay rate.
- The idea is to study $(\tau^\mp \to h^\mp_{\rm CP}\nu\ ;\ \tau^\pm \to \rho^\pm\nu)$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

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

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

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

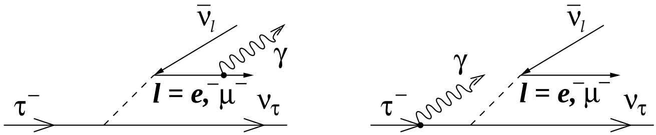
$$\mathcal{F} = D_0A_0A' - D_{ij}B_{0i}B'_j,\ \mathcal{G} = D_0A_1A' - D_{ij}B_{1i}B'_j$$



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

$\eta_{\rm CP}$ **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.

Study of radiative leptonic decays



Photon carries information about spin state of outgoing lepton, as a result two additional Michel-like parameters, $\bar{\eta}$ and $\xi\kappa$, can be extracted:

$$\frac{d\Gamma(L^{\mp})}{dxdyd\Omega_\ell d\Omega_\gamma} = f_0(x,y) + \bar{\eta} f_1(x,y) \pm \xi \left\{ \cos\theta_\ell \left(h_0(x,y) + \kappa h_1(x,y)\right) + \cos\theta_\gamma \left(g_0(x,y) + \kappa g_1(x,y)\right) \right\}$$

	Belle+BaBar	Belle II
$N_{sel}(e^{\mp};\rho^{\pm}),\ 10^6$	0.87	28.2
$N_{sel}(\mu^{\mp};\rho^{\pm}),\ 10^6$	0.18	5.8

We are measuring $\bar{\eta}$ and $\xi\kappa$ in τ decays at Belle. The expected accuracy is 7.7% for the $\xi\kappa$ and 9.8% for the $\bar{\eta}$. At Belle II the expected statistical uncertainties of $\xi\kappa$ and $\bar{\eta}$ are 1.1% and 1.4%, respectively.

N. Shimizu et al., Poster talk at the Tau-2014 conf., Aachen, Germany, 15-19 September, 2014.

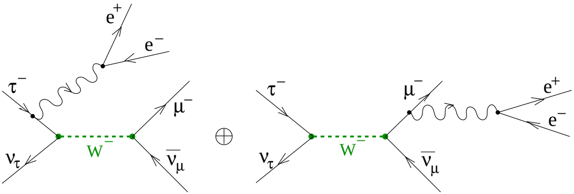
Up to now $\bar{\eta}$ and $\xi\kappa$ were measured only in $\mu^- \to e^- \nu_\mu \bar{\nu}_e \gamma$ decays:

PDG: $\bar{\eta} = -0.014 \pm 0.090$: W. Eichenberger *et al.*, Nucl. Phys. A **412** (1984) 523.

CONF: $\bar{\eta} = -0.084 \pm 0.060$: D. Pocanic [PIBETA], AIP Conf. Proc. **1423** (2012) 273.

PDG(ξ'): $\xi\kappa = 0.000 \pm 0.010$: H. Burkard *et al.* [CNTR], Phys. Lett. B **150** (1985) 242.

Tau decays into 5 leptons



D. A. Dicus and R. Vega, Phys. Lett. B **338** (1994) 341.

M. S. Alam *et al.* [CLEO Collaboration], Phys. Rev. Lett. **76** (1996) 2637.

Mode	$\mathcal{B}_{theory}$, 10^{-7}	$\mathcal{B}_{CLEO}$, 10^{-5}
$e^\mp e^+ e^- 2\nu$	415 ± 6	$2.7^{+1.6}_{-1.2}$
$\mu^\mp e^+ e^- 2\nu$	197 ± 2	< 3.2(90% CL)
$e^\mp \mu^+ \mu^- 2\nu$	1.257 ± 0.003	
$\mu^\mp \mu^+ \mu^- 2\nu$	1.190 ± 0.002	

	Belle	Belle II
$N_{sel}(e^\mp e^+ e^-;\ 1\,\text{prong}^\pm)$	1750	87500
$N_{sel}(\mu^\mp e^+ e^-;\ 1\,\text{prong}^\pm)$	600	30000
$N_{sel}(e^\mp \mu^+ \mu^-;\ 1\,\text{prong}^\pm)$	2	100
$N_{sel}(\mu^\mp \mu^+ \mu^-;\ 1\,\text{prong}^\pm)$	2	100

A. Kersch, N. Kraus and R. Engfer [SINDRUM], Nucl. Phys. A **485** (1988) 606.

$$\frac{d\Gamma(\tau)}{d\mathcal{PS}} = Q_{LL} d_1 + Q_{LR} d_2 + Q_{RL} d_3 + Q_{RR} d_4 + B_{RL} d_5 + B_{LR} d_6$$

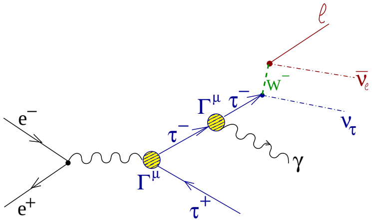
Up to now Q_{LL}, Q_{LR}, Q_{RL}, Q_{RR}, B_{RL}, B_{LR} were measured only in muon decays ($\mu^- \to e^- e^- e^+ \nu_\mu \bar{\nu}_e$) with the accuracy of about $10 \div 20\%$. In τ decays these parameters can be measured with the accuracy of $\sim 20\%$ at Belle, and $3 \div 5\%$ at Belle II.

a_τ and EDM in radiative leptonic decays

$$\vec{\mu}_\tau = g_\tau \frac{e}{2m}\vec{S}$$

$$a_\tau = (g_\tau - 2)/2$$

QED LO: $a_\tau = \frac{\alpha}{2\pi}$ (J. Schwinger '48)



$$\Gamma^\mu = \gamma^\mu F_1(q^2) + \frac{1}{2m_\tau}(iF_2(q^2) + F_3(q^2)\gamma^5)\sigma^{\mu\nu}q_\nu + (q^2\gamma^\mu - \hat{q}q^\mu)\gamma^5 F_A(q^2)$$

$$F_1(0) = 1,\ a_\tau = F_2(0),\ d_\tau = \frac{e}{2m_\tau}F_3(0)$$

- In the SM leptons are considered as pointlike objects. Therefore the observation of a deviation of the magnetic moments of the leptons from their SM values would open a window into physics beyond the SM.
- In comparison with a_e and a_μ, the τ anomalous magnetic moment (a_τ) is much better suited to observe NP effects, which are expected to be $\sim m_\ell^2/\Lambda^2$, where Λ is the NP scale, so $a_\tau/a_\mu = (m_\tau/m_\mu)^2 \approx 283$.

$$a_\tau^{SM} = 117721(5) \times 10^{-8}$$

S. Eidelman and M. Passera, Mod. Phys. Lett. A **22** (2007) 159 [hep-ph/0701260].

a_τ and d_τ in $\tau \to \ell\nu\nu\gamma$

M. L. Laursen *et al.*, Phys. Rev. D **29** (1984) 2652 [Erratum-ibid. D **56** (1997) 3155].

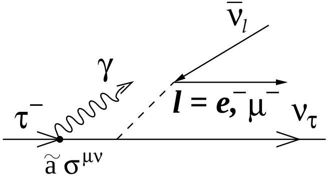
It was suggested to search for the a_τ in the $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau \gamma$ using the phenomenon of radiation zero: in the vicinity of $cos(\ell,\gamma) = -1$, $x = 2E_\ell/m_\tau = 1 + \frac{m_\ell^2}{m_\tau^2}$ term $\sim a_\tau^2$ dominates.

Effective interaction

$$\mathcal{L}_{eff} = c_a \frac{e}{4\Lambda}\,\bar{\tau}\sigma_{\mu\nu}\tau F^{\mu\nu} - c_d \frac{i}{2\Lambda}\,\bar{\tau}\sigma_{\mu\nu}\gamma_5\tau F^{\mu\nu},$$

$$a_\tau = \frac{\alpha}{2\pi} + \mathrm{Re}(c_a)\frac{m_\tau}{\Lambda},\ d_\tau = \mathrm{Re}(c_d)\frac{1}{\Lambda},$$

$$\tilde{a}_\tau = c_a\frac{m_\tau}{\Lambda},\ \tilde{d}_\tau = c_d\frac{m_\tau}{e\Lambda}$$



$$\frac{d^6\Gamma}{dxdyd\Omega_\ell d\Omega_\gamma} = G(x,y,c) + \vec{\zeta}\cdot\vec{n}_\ell J(x,y,c) + \vec{\zeta}\cdot\vec{n}_\gamma K(x,y,c) + \vec{\zeta}\cdot(\vec{n}_\ell \times \vec{n}_\gamma)L(x,y,c),\ c = \vec{n}_\ell\cdot\vec{n}_\gamma,$$

M. Passera, M. Fael (U. of Padova, Italy), L. Mercolli (Princeton U., USA)

In our feasibility study $\Re(\tilde{a}_\tau)$, $\Im(\tilde{a}_\tau)$, $\Re(\tilde{d}_\tau)$, $\Im(\tilde{d}_\tau)$ parameters were extracted in the unbinned maximum likelihood fit of $(\tau^\mp \to \ell^\mp\nu\nu\gamma;\ \tau^\pm \to \rho^\pm\nu)$ (ρ-tag) and $(\tau^\mp \to \ell^\mp\nu\nu\gamma;\ \tau^\pm \to h^\pm\nu)$, $h = e,\ \mu,\ \pi,\ \pi\pi^0,\ \pi 2\pi^0, 3\pi$ (full tag) events in the 12D phase space.

Sensitivity on $\tilde{a}_\tau$ and $\tilde{d}_\tau$ at Belle/Belle II

	$\Re(\tilde{a}_\tau)$	$\Im(\tilde{a}_\tau)$	$\Re(\tilde{d}_\tau)$	$\Im(\tilde{d}_\tau)$
Belle (ρ-tag)	0.16	0.16	0.15	0.046
Belle II (ρ-tag)	0.023	0.023	0.021	0.007
Belle (full tag)	0.085	0.085	0.080	0.024
Belle II (full tag)	0.012	0.012	0.011	0.003
DELPHI	0.017	—	—	—
Belle	—	—	0.0015	0.0008

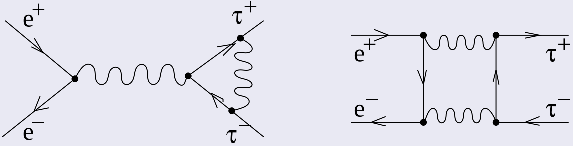
J. Abdallah *et al.* [DELPHI Collaboration], Eur. Phys. J. C **35** (2004) 159

$-0.052 < a_\tau < 0.013\,(CL = 95\%)$ in $e^+e^- \to e^+e^-\tau^+\tau^-$

K. Inami *et al.* [Belle Collaboration], Phys. Lett. B **551** (2003) 16.

$\Re(d_\tau)/\Im(d_\tau) = (1.15 \pm 1.70)/(-0.83 \pm 0.86) \times 10^{-17}$ e·cm, in $e^+e^- \to \tau^+\tau^-$

To measure a_τ in the $\tau^+\tau^-$ production vertex the procedure to take into account box diagrams should be developed.



Search for heavy Majorana neutrino in τ decays I

C. Greub, D. Wyler and W. Fetscher, Phys. Lett. B **324** (1994) 109 [Erratum-ibid. B **329** (1994) 526]

In the case of nonzero neutrino mass additional Michel parameters, λ and σ, appear in the differential decay width of $\tau \to \ell\nu\nu$ with additional suppression factor of m_ν/m_τ. But even ordinary Michel parameters can be used to search for the effect of Majorana neutrino: M. Doi, T. Kotani and H. Nishiura, Prog. Theor. Phys. **118** (2007) 1069 [Erratum-ibid. **122** (2009) 805].

$$\Delta\rho \sim |g^V_{LR}|^2(\overline{v_\mu}^2 + |\overline{w_{e\mu}}|^2) + |g^V_{RL}|^2(\overline{v_e}^2 + |\overline{w_{e\mu h}}|^2), \;\; \Delta\eta \sim g^V_{RR}\mathrm{Re}(\overline{w_{e\mu}}^*\overline{w_{e\mu h}})$$

,

$$\Delta\xi \sim -|g^V_{RR}|^2\overline{v_e}^2\overline{v_\mu}^2, \;\; \Delta\delta \sim |g^V_{LR}|^2(\overline{v_\mu}^2 + |\overline{w_{e\mu}}|^2) - |g^V_{RL}|^2(\overline{v_e}^2 + |\overline{w_{e\mu h}}|^2)$$

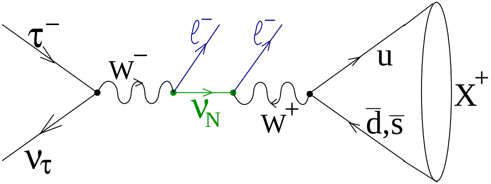
$$.\ \sum_j |U_{\ell j}|^2 = 1 - \overline{u_\ell}^2, \;\; \sum_j |V_{\ell j}|^2 = \overline{v_\ell}^2, \;\; \ell = e, \; \mu,$$

$$\sum_j U_{ej}V_{\mu j} = \overline{w_{e\mu}}, \;\; \sum_k V_{ek}U_{\mu k} = \overline{w_{e\mu h}},$$

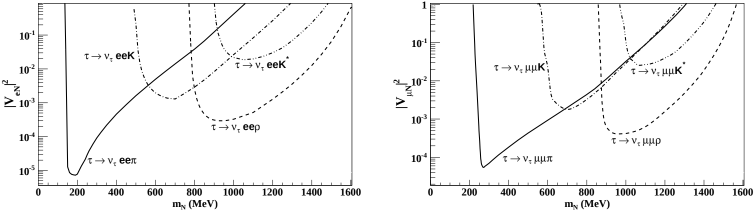
$$\overline{u_\ell}^2 \sim \overline{v_\ell}^2 \sim \mathcal{O}((m_{\nu D}/m_{\nu R})^2), \;\; \overline{w_{e\mu}} \sim \overline{w_{e\mu h}} \sim \mathcal{O}(m_{\nu D}/m_{\nu R}),$$

where: $U_{\ell j}/V_{\ell j}$ - left/right-chirality lepton mixing matrix, $m_{\nu D}$ and $m_{\nu R}$ are Dirac-type and right-chirality Majorana-type elements of the neutrino mass matrix.

$\tau^- \to \ell^-\ell^- X^+ \nu_\tau$ ($\ell = e,\ \nu$; $X = \pi,\ K,\ \rho,\ K^*$) decays with $|\Delta L| = 2$ can be induced by the exchange of Majorana neutrinos.



G. Lopez Castro and N. Quintero, Phys. Rev. D **85** (2012) 076006.



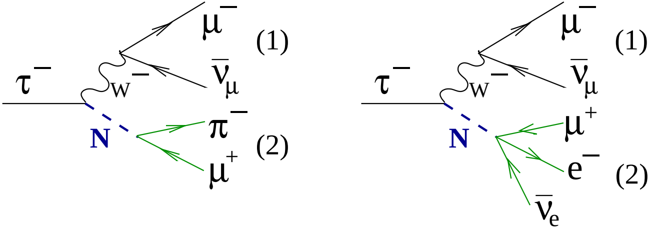
In the case of the resonant mechanism where the contribution of one heavy Majorana neutrino dominates and $\mathcal{B}$ upper limits of $\mathcal{O}(10{-}7)$ (which can be reached at Belle II) the constraints on the $|V_{\ell N}|^2$ vs m_N plane can be obtained (competitive to the constraints from B and D decays).

Search for sterile neutrino in τ decays

C. Dib *et al.*, Phys. Rev. D **85** (2012) 011301.

To clarify MiniBooNE and LSND anomalies it was suggested to search for the long-living sterile neutrino.

400 MeV$\lesssim m_N \lesssim$ 600 MeV, $1\times10^{-3} \lesssim |U_{\mu N}|^2 \lesssim 4\times10^{-3}$, $\tau_N \lesssim 1\times10^{-9}$ s.



To explain anomaly the branching fractions must be:

$$\mathcal{B}(\tau^- \to \{\mu^-\bar{\nu}_\mu\}_1\{\mu^+\pi^-\}_2) = 2.0\times10^{-9} \div 1.3\times10^{-5},$$
$$\mathcal{B}(\tau^- \to \{\mu^-\bar{\nu}_\mu\}_1\{\mu^+e^-\bar{\nu}_e\}_2) = 2.1\times10^{-8} \div 8.2\times10^{-5}.$$

The main signature is the displaced vertex (2) with $L = 0.6 \div 30$ cm.

Sterile neutrino can be also searched for in radiative leptonic decays:

$\tau^- \to \ell^-\bar{\nu}_\ell N,\ N \to \gamma\nu$, i.e. constraints can be obtained from Michel parameters.