Experimental review of τ lepton studies at the B factories

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2. **Precision studies of τ properties**
3. **CPV in hadronic τ decays**
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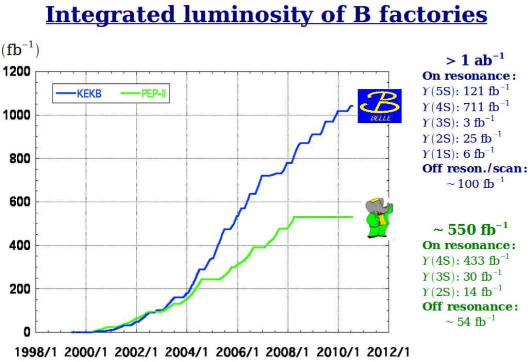
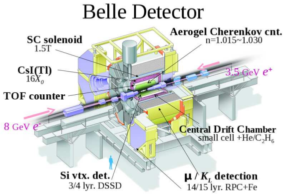
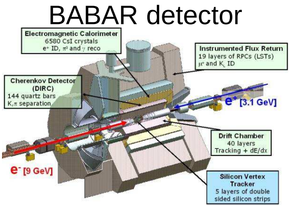
Introduction

- The world largest statistics of τ leptons collected by e^+e^- B factories (Belle and *BABAR*) 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, etc. should be measured experimentally as precisely as possible in order to test SM and search for the effects of New Physics.
- 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: e^+e^- B factories







$\sigma(b\bar{b}) = 1.05$ nb $N_{b\bar{b}} = 1.2 \times 10^9$
$\sigma(c\bar{c}) = 1.30$ nb $N_{c\bar{c}} = 2.0 \times 10^9$
$\sigma(\tau\tau) = 0.92$ 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 at e^+e^- B factories

- **Michel parameters in $\tau \to \ell\nu\nu$ (ρ, η, ξ, δ) at Belle**: arXiv:1409.4969
- **Study of the radiative leptonic decays $\tau \to \ell\nu\nu\gamma$:**

  BABAR: Measurement of $\mathcal{B}(\tau \to \ell\nu\nu\gamma)$; PRD 91, 051103(R) (2015)

  Belle(prelim.): $\bar{\eta} = -1.3 \pm 1.5 \pm 0.8$, $\xi\kappa = 0.5 \pm 0.4 \pm 0.2$; arXiv:1609.08280
- **Lepton universality with $\tau \to \ell\nu\nu$ and $\tau \to h\nu$ (h=π,K) at *BABAR*:**

  $\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020$, $\left(\frac{g_\tau}{g_\mu}\right)_\mathrm{h} = 0.9850 \pm 0.0054$; PRL 105, 051602 (2010)
- **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: $\mathrm{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$ $e\cdot$cm, $\mathrm{Im}(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17}$ $e\cdot$cm;
  PLB 551, 16 (2003) ($\int Ldt = 29.5$ fb^{-1}) We are working on 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)

Michel parameters

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:

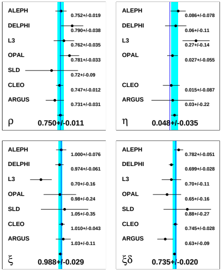
$$\frac{d\Gamma(\tau^\mp)}{d\Omega dx} = \frac{4G_F^2 M_\tau E_{\max}^4}{(2\pi)^4} \sqrt{x^2 - x_0^2} \Bigg(x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

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

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

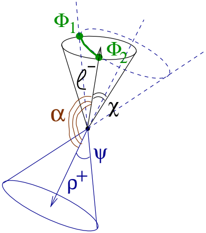


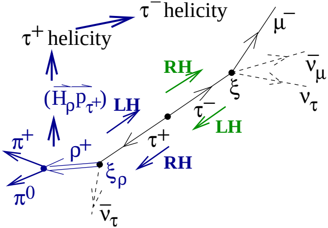
With $\times 300$ Belle statistics we can improve MP uncertainties by one order of magnitude

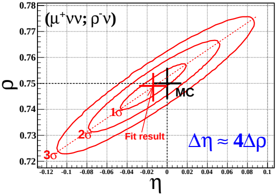
In BSM models the couplings to τ are expected to be enhanced in comparison with μ.
Also contribution from New Physics in τ decays can be amplified by $(\frac{m_\tau}{m_\mu})^n$.

- **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.

Effect of τ spin-spin correlation is used to measure ξ and δ MP.
Events of the $(\tau^{\mp} \to \ell^{\mp}\nu\nu;\ \tau^{\pm} \to \rho^{\pm}\nu)$ 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.







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

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

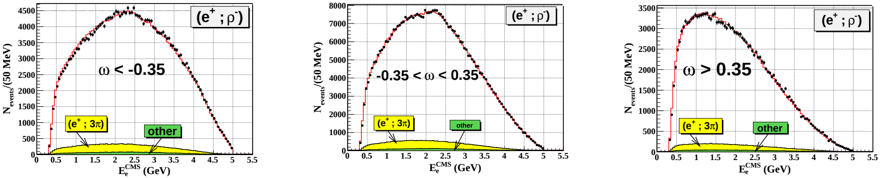
$$L = \prod_{k=1}^{N} \mathcal{P}^{(k)},\ \mathcal{P}^{(k)} = \mathcal{F}(\vec{z}^{(k)})/\mathcal{N}(\vec{\Theta}),\ \mathcal{N}(\vec{\Theta}) = \int \mathcal{F}(\vec{z})d\vec{z},\ \vec{\Theta} = (1,\rho,\eta,\xi_\rho\xi_\ell,\xi_\rho\xi_\ell\delta_\ell)$$

$$\boldsymbol{\mathcal{P}}_{\mathbf{total}} = (1 - \sum_{i=1}^{4}\lambda_i)\boldsymbol{\mathcal{P}}^{\ell-\rho}_{signal} + \lambda_1\mathcal{P}^{\ell-3\pi}_{bg} + \lambda_2\mathcal{P}^{\pi-\rho}_{bg} + \lambda_3\mathcal{P}^{\rho-\rho}_{bg} + \lambda_4\boldsymbol{\mathcal{P}}^{other}_{bg}\ \text{(MC)}$$

MP are extracted in the unbinned maximum likelihood fit of $(\ell\nu\nu;\ \rho\nu)$ 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.

Data fits and systematic uncertainties

Helicity sensitive variable $\omega = \frac{1}{\Phi_2 - \Phi_1} \int_{\Phi_1}^{\Phi_2} (\vec{H}_{\rho^\pm}, \vec{n}_{\tau^\pm}) d\Phi = < (\vec{H}_{\rho^\pm}, \vec{n}_{\tau^\pm}) >_{\Phi_\tau}$



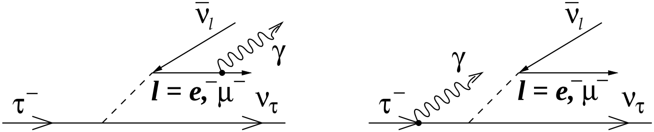
Spin-spin correlation manifests itself through momentum-momentum correlations of final lepton and pions.

Source	$\Delta(\rho)$, %	$\Delta(\eta)$, %	$\Delta(\xi_\rho \xi)$, %	$\Delta(\xi_\rho \xi \delta)$, %
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
Background	0.20	0.60	0.20	0.20
Apparatus corrections				
Resolution $\oplus$ brems.	0.10	0.33	0.11	0.19
$\sigma(E_{\rm beam})$	0.07	0.25	0.03	0.15
Normalization				
$\Delta\mathcal{N}$	0.11	0.50	0.17	0.13
without Data/MC corr.	**0.29**	**0.95**	**0.38**	**0.38**
trigger eff. corr.	**$\sim$ 1**	**$\sim$ 2**	**$\sim$ 3**	**$\sim$ 3**

We are working on the Data/MC efficiency corrections (trigger, ℓID, track rec., π^0 rec.).

Michel parameters in $\tau \to \ell\nu\nu\gamma$, $(\ell = e, \mu)$ (I)

C. Fronsdal and H. Uberall, Phys. Rev. **113** (1959) 654. ($m_\ell = 0$)
A. B. Arbuzov and T. V. Kopylova, JHEP **1609** (2016) 109. ($m_\ell \neq 0$)



Photon carries information about spin state of outgoing lepton, as a result two additional parameters, $\bar{\eta}$ and $\xi\kappa$, can be extracted.
These parameters were measured in τ decays at Belle for the first time.

$$\frac{d\Gamma(\tau^\mp \to \ell^\mp \nu_\ell \nu_\tau \gamma)}{dx\, dy\, d\Omega_\ell\, d\Omega_\gamma} = \Gamma_0 \frac{\alpha}{64\pi^3} \frac{\beta_\ell}{y} \left[F(x,y,d) \pm P_\tau \left(\beta_\ell \cos\theta_\ell G(x,y,d) + \cos\theta_\gamma H(x,y,d) \right) \right],$$

$$\Gamma_0 = G_F^2 m_\tau^5/192\pi^3,\ \beta_\ell = \sqrt{1 - m_\ell^2/E_\ell^2},\ x = 2E_\ell/m_\tau,\ y = 2E_\gamma/m_\tau,\ d = 1 - \beta_\ell \cos\theta_{\ell\gamma}$$

$$F = F_0 + \bar{\eta} F_1,\ G = G_0 + \xi\kappa G_1,\ H = H_0 + \xi\kappa H_1,\ \frac{d\sigma(\ell^\mp \nu\nu\gamma, \rho^\pm \nu)}{dE_\ell^* d\Omega_\ell^* dE_\gamma^* d\Omega_\gamma^* d\Omega_\rho^* dm_{\pi\pi}^2 d\tilde{\Omega}_\pi d\Omega_\tau} = A_0 + \bar{\eta} A_1 + \xi\kappa A_2$$

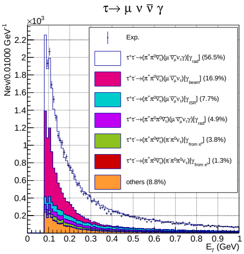
$$\mathcal{F}(\vec{z}) = \frac{d\sigma(\ell^\mp \nu\nu\gamma, \rho^\pm \nu)}{dp_\ell d\Omega_\ell dp_\gamma d\Omega_\gamma dp_\rho d\Omega_\rho dm_{\pi\pi}^2 d\tilde{\Omega}_\pi} = \int_{\Phi_1}^{\Phi_2} \frac{d\sigma(\ell^\mp \nu\nu\gamma, \rho^\pm \nu)}{dE_\ell^* d\Omega_\ell^* dE_\gamma^* d\Omega_\gamma^* d\Omega_\rho^* dm_{\pi\pi}^2 d\tilde{\Omega}_\pi d\Omega_\tau} |\text{JACOBIAN}|\, d\Phi_\tau$$

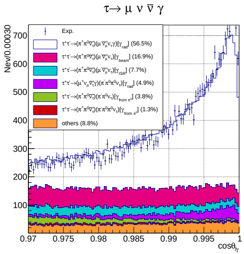
$$L = \prod_{k=1}^{N} \mathcal{P}^{(k)},\ \mathcal{P}^{(k)} = \frac{\mathcal{F}(\vec{z}^{(k)})}{\mathcal{N}(\vec{\Theta})} = \frac{\mathcal{F}_0 + \mathcal{F}_1 \bar{\eta} + \mathcal{F}_2 \xi\delta}{\mathcal{N}_0 + \mathcal{N}_1 \bar{\eta} + \mathcal{N}_2 \xi\delta},\ \mathcal{N}_k = \int \mathcal{F}_k(\vec{z}) d\vec{z},\ (k = 0, 1, 2)$$

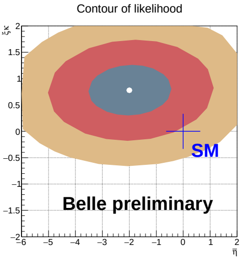
$\bar{\eta}$ and $\xi\delta$ are extracted in the unbinned maximum likelihood fit of $(\ell\nu\nu\gamma;\ \rho\nu)$ events in the 12D phase space in CMS.

Michel parameters in $\tau \to \ell\nu\nu\gamma$, ($\ell = e, \mu$) (II)

$N_{\tau\tau} = 646 \times 10^6$, **selected: 71171** ($\mu\nu\nu\gamma$; $\rho\nu$) **and 776834** ($e\nu\nu\gamma$; $\rho\nu$) **events**







Source	$\sigma^e_{\bar{\eta}}$	$\sigma^e_{\xi\kappa}$	$\sigma^\mu_{\bar{\eta}}$	$\sigma^\mu_{\xi\kappa}$
Normalization	4.3	0.94	0.15	0.04
Background PDF	2.5	0.24	0.67	0.22
Branching ratios	3.8	0.05	0.25	0.01
Cluster merge in ECL	2.2	0.46	0.02	0.06
Detector resolution	0.74	0.20	0.22	0.02
Data/MC eff. corr.	1.9	0.14	0.04	0.04
Total	7.0	1.1	0.76	0.24

Belle preliminary

$$\bar{\eta} = -\mathbf{1.3} \pm \mathbf{1.5} \pm \mathbf{0.8}$$

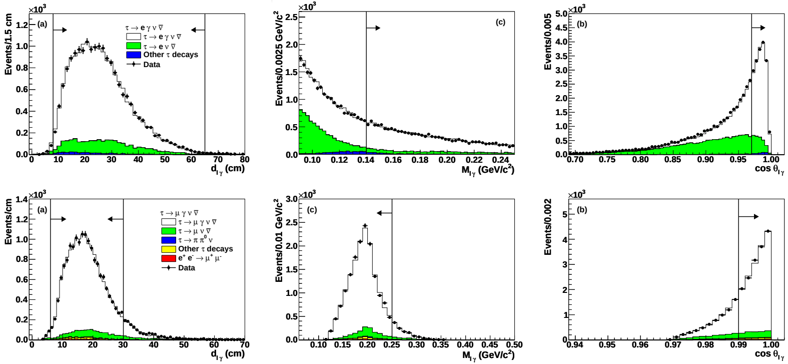
$$\xi\kappa = \mathbf{0.5} \pm \mathbf{0.4} \pm \mathbf{0.2}$$

Measurement of $\mathcal{B}(\tau \to \ell\nu\nu\gamma)$ at *BABAR* (I)

$$\int \boldsymbol{Ldt} = \mathbf{431\ fb^{-1}}$$

Selections:

- 2-track events with zero net charge and 1 photon with $E_\gamma > 50$ MeV;
- 0.9<thrust<0.995, signal hemisphere: $\ell + \gamma$, tag hemisphere: track+neutrals;
- reject $\ell^\mp - \ell^\pm$ events, $E_{\rm tot} < 9$ GeV, distance between track and photon clusters $d_{\ell\gamma} < 100$ cm.



$\boldsymbol{e\nu\nu\gamma}$	$0.22 \le E_\gamma \le 2.0$ GeV, $M_{e\gamma} \ge 0.14$ GeV/c^2, $\cos\theta_{e\gamma} \ge 0.97$, $8 \le d_{e\gamma} \le 65$ cm
$\boldsymbol{\mu\nu\nu\gamma}$	$0.10 \le E_\gamma \le 2.5$ GeV, $M_{\mu\gamma} \le 0.25$ GeV/c^2, $\cos\theta_{\mu\gamma} \ge 0.99$, $6 \le d_{\mu\gamma} \le 30$ cm

$$\boldsymbol{N_{\rm sel}(\mu\nu\nu\gamma) = 15688 \pm 125 \quad N_{\rm sel}(e\nu\nu\gamma) = 18149 \pm 135}$$

Measurement of $\mathcal{B}(\tau \to \ell\nu\nu\gamma)$ at *BABAR* (II)

$$\mathcal{B} = \frac{N_{\rm sel}(1 - f_{\rm bg})}{2\sigma_{\tau\tau}\mathcal{L}\varepsilon}$$

	$\mu\nu\nu\gamma$	$e\nu\nu\gamma$
ε (%)	0.480 ± 0.010	0.105 ± 0.003
$f_{\rm bg}$	0.102 ± 0.002	0.156 ± 0.003

	$\tau \to \mu\nu\nu\gamma$	$\tau \to e\nu\nu\gamma$
Photon efficiency	1.8	1.8
Particle identification	1.5	1.5
Background evaluation	0.9	0.7
BF	0.7	0.7
Luminosity and cross section	0.6	0.6
MC statistics	0.5	0.6
Selection criteria	0.5	0.5
Trigger selection	0.5	0.6
Track reconstruction	0.3	0.3
Total	2.8	2.8

$$\mathcal{B}(\tau \to \mu\nu\nu\gamma)[E^*_\gamma > 10\,\mathrm{MeV}] = (3.69 \pm 0.03 \pm 0.10) \times 10^{-3}$$

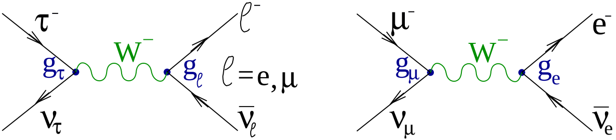
$$\mathcal{B}(\tau \to e\nu\nu\gamma)[E^*_\gamma > 10\,\mathrm{MeV}] = (1.847 \pm 0.015 \pm 0.052) \times 10^{-2}$$

Measured branching ratios agree with the LO predictions ($\mathcal{B}(\mu\nu\nu\gamma) = 3.663 \times 10^{-3}$, $\mathcal{B}(e\nu\nu\gamma) = 1.834 \times 10^{-2}$), however the LO+NLO prediction for the $\tau \to e\nu\nu\gamma$ ($\mathcal{B}(e\nu\nu\gamma) = 1.645 \times 10^{-2}$) differs from the experimental result by **3.5σ**. It is important to embed NLO corrections to the MC generator (TAUOLA) of the radiative leptonic decay. Also background from the doubly-radiative leptonic decays should be properly studied and subtracted.

M. Fael, L. Mercolli and M. Passera, JHEP 1507 (2015) 153.

Lepton universality in the SM

$$g_e = g_\mu = g_\tau$$



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

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

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

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

$$\frac{g_\tau}{g_e} = \sqrt{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau(\gamma)) \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\rm corr}(m_\mu, m_e)}{F_{\rm corr}(m_\tau, m_\mu)}},\ \frac{\mathbf{g}_\tau}{\mathbf{g}_e} = \mathbf{1.0029 \pm 0.0015}\ \text{(HFAG2017)}$$

$$\frac{g_\tau}{g_\mu} = \sqrt{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau(\gamma)) \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\rm corr}(m_\mu, m_e)}{F_{\rm corr}(m_\tau, m_e)}},\ \frac{\mathbf{g}_\tau}{\mathbf{g}_\mu} = \mathbf{1.0010 \pm 0.0015}\ \text{(HFAG2017)}$$

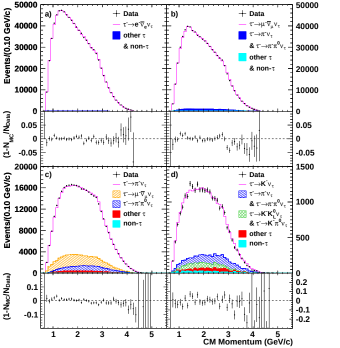
$$\frac{g_\mu}{g_e} = \sqrt{\frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau(\gamma))}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau(\gamma))} \frac{F_{\rm corr}(m_\tau, m_e)}{F_{\rm corr}(m_\tau, m_\mu)}},\ \frac{\mathbf{g}_\mu}{\mathbf{g}_e} = \mathbf{1.0019 \pm 0.0014}\ \text{(HFAG2017)}$$

Test of lepton universality at *BABAR* (I)

$$\int Ldt = 467\ \mathrm{fb}^{-1}$$

Selections:

- 4-track events with zero net charge;
- $0.1\sqrt{s} < E^{\rm CMS}_{\rm miss} < 0.7\sqrt{s}$, $|\cos(\theta^{\rm CMS}_{\rm miss})| < 0.7$
- thrust> 0.9, signal hemisphere: $\ell/h(\ell = e, \mu;\ h = \pi, K)$, tag hemisphere: $\tau \to \pi\pi\pi\nu$;
- signal hemisphere: $E^{LAB}_{\rm extra\gamma} < \{1.0,\ 0.5,\ 0.2,\ 0.2\}$ GeV for $\{e,\ \mu,\ \pi,\ K\}$, respectively



	μ	π	K
$\mathbf{N}^{\rm D}$	731102	369091	25123
Purity	97.3%	78.7%	76.6%
Total Efficiency	0.485%	0.324%	0.330%
Particle ID Efficiency	74.5%	74.6%	84.6%
Systematic uncertainties:			
Particle ID	0.32	0.51	0.94
Detector response	0.08	0.64	0.54
Backgrounds	0.08	0.44	0.85
Trigger	0.10	0.10	0.10
$\pi^-\pi^-\pi^+$ modelling	0.01	0.07	0.27
Radiation	0.04	0.10	0.04
$\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$	0.05	0.15	0.40
$\mathcal{L}\sigma_{\tau\tau}$	0.02	0.39	0.20
Total [%]	**0.36**	**1.0**	**1.5**

$\boldsymbol{\tau \to e\nu\nu}$: $N_{\rm sel} = 884426$, $\varepsilon = (0.589 \pm 0.010)\%$, purity is $(99.69 \pm 0.06)\%$

Test of lepton universality at *BABAR* (II)

$$R_\mu = \frac{\mathcal{B}(\tau \to \mu\nu\nu)}{\mathcal{B}(\tau \to e\nu\nu)} = 0.9796 \pm 0.0016 \pm 0.0036$$

$$R_\pi = \frac{\mathcal{B}(\tau \to \pi\nu)}{\mathcal{B}(\tau \to e\nu\nu)} = 0.5945 \pm 0.0014 \pm 0.0061$$

$$R_K = \frac{\mathcal{B}(\tau \to K\nu)}{\mathcal{B}(\tau \to e\nu\nu)} = 0.03882 \pm 0.00032 \pm 0.00057$$

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{F_{\rm corr}(m_\tau, m_e)}{F_{\rm corr}(m_\tau, m_\mu)}} = 1.0036 \pm 0.0020$$

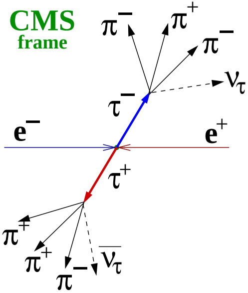
$$\left(\frac{g_\tau}{g_\mu}\right)_h^2 = \frac{\mathcal{B}(\tau \to h\nu_\tau)}{\mathcal{B}(h \to \mu\nu_\mu)} \frac{2m_h m_\mu^2 \tau_h}{(1+\delta_h)m_\tau^3 \tau_\tau} \left(\frac{1-m_\mu^2/m_h^2}{1-m_h^2/m_\tau^2}\right)^2$$

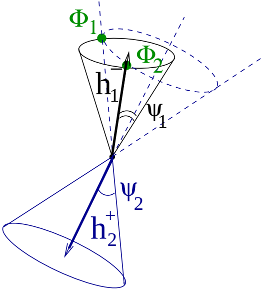
$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9856 \pm 0.0057, \quad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.9827 \pm 0.0086$$

$$\left(\frac{g_\tau}{g_\mu}\right)_h = 0.9850 \pm 0.0054 \; (2.8\sigma \text{ away from SM})$$

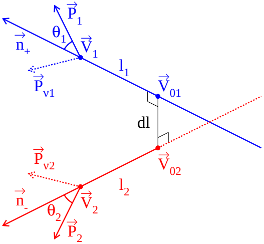
$$\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 1.0000 \pm 0.0014 \; (\text{HFAG2017})$$

Use the data sample of $\int L dt = 711$ fb^{-1} with $N_{\tau\tau} = 650 \times 10^6$
Analysis of $e^+e^- \to \tau^+\tau^- \to (\pi^+\pi^+\pi^-\bar{\nu}_\tau,\ \pi^+\pi^-\pi^-\nu_\tau)$ events.





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



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

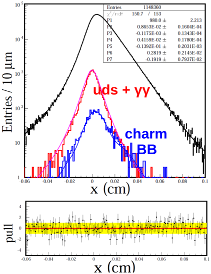
- τ momentum direction is determined with two-fold ambiguity in CMS, for the analysis we use the average axis.
- Asymmetric-energy layout of experiment allows us to determine $\tau^+\tau^-$ production point in LAB independently from the position of beam IP.

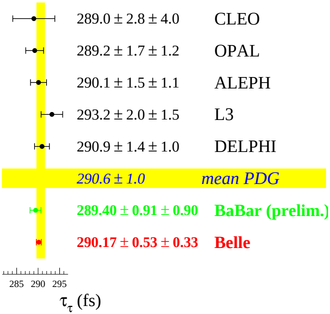
1148360 events were selected with $\sim$2% background contamination, the main background comes from $e^+e^- \to q\bar{q}$ ($q =$u, d, s).

Decay length PDF

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

- λ_τ - estimator of $c\tau_\tau$;
- $R(x;\vec{P})$ - detector resolution function;
- $\mathcal{N}_{uds}$, $\mathcal{P}_{cb}(x)$ - background PDFs from MC





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**

$$c\tau_\tau = (86.99 \pm 0.16(\text{stat}) \pm 0.10(\text{syst}))\ \mu\text{m}.$$
$$\tau_\tau = (290.17 \pm 0.53(\text{stat}) \pm 0.33(\text{syst}))\ \text{fs}.$$
$$|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\text{average}} < 7.0 \times 10^{-3}\ \text{at}\ 90\%\ \text{CL}.$$

Hadronic τ decays

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

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

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

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

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

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

- 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

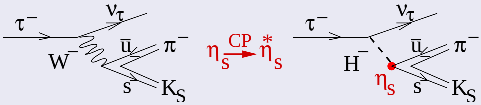
$$A_{\rm CP} = \frac{\Gamma(\tau^+ \to \pi^+ K^0_S(\geq 0\pi^0)\bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K^0_S(\geq 0\pi^0)\nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K^0_S(\geq 0\pi^0)\bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K^0_S(\geq 0\pi^0)\nu_\tau)} = (-0.36 \pm 0.23 \pm 0.11)\%$$

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

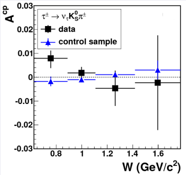
II. CPV in $\tau^- \to K^0_S \pi^- \nu_\tau$ at Belle (Phys. Rev. Lett. 107, 131801 (2011)) $\int$Ldt=699 fb^{-1}

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

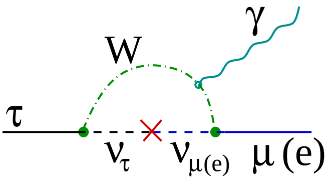
$$A_{\rm CP}(W) = \frac{\int \cos\beta\cos\psi \left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}{\frac{1}{2}\int \left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega} \simeq \langle\cos\beta\cos\psi\rangle_{\tau^-} - \langle\cos\beta\cos\psi\rangle_{\tau^+}$$



$|Im(\eta_S)| < 0.026$



Lepton-flavor-violating (LFV) τ decays

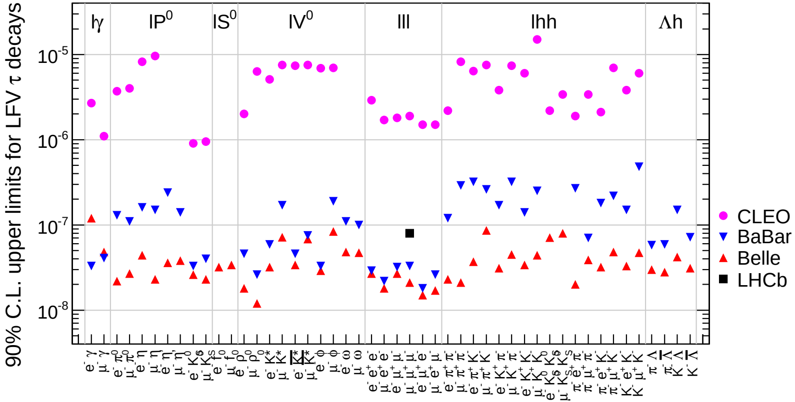


Model	$\mathcal{B}(\tau \to \mu\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
mSUGRA+seesaw	10^{-8}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-8}

- 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



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

UL for BNV and LNV τ decays with protons from LHCb: PLB 724, 36 (2013)

Summary

- **The world largest statistics of τ leptons collected by Belle and *BABAR* opens new era in the precision tests of the Standard Model and search for the effects of New Physics.**
- Complementary study of leptonic τ decays at *BABAR* and Belle. *BABAR* measured precisely the ratio of the leptonic branching ratios to test lepton universality. While Belle is working on the precision measurement of Michel parameters.
- *BABAR* and Belle performed complementary study of the radiative leptonic τ decay ($\tau \to \ell\nu\nu\gamma$ ($\ell = e,\ \mu$)):
  - With the statistics of 431 fb^{-1} branching fractions were measured with the relative accuracy better than 3% by *BABAR*:

$$\mathcal{B}(\tau \to \mu\nu\nu\gamma)[E^*_\gamma > 10\,\mathrm{MeV}] = (3.69 \pm 0.03 \pm 0.10) \times 10^{-3}$$
$$\mathcal{B}(\tau \to e\nu\nu\gamma)[E^*_\gamma > 10\,\mathrm{MeV}] = (1.847 \pm 0.015 \pm 0.052) \times 10^{-2}$$

  - For the first time Belle measured Michel parameters, $\bar{\eta}$ and $\xi\kappa$ in $\tau \to \ell\nu\nu\gamma$ decays on the statistics of 703 fb^{-1}:

$$\bar{\eta} = -1.3 \pm 1.5 \pm 0.8$$
$$\xi\kappa = 0.5 \pm 0.4 \pm 0.2$$

  An importance of the NLO corrections and doubly-radiative decays was realized for the precision measurement of the branching ratios.
- Both fundamental parameters of τ, needed for the precision tests of the SM, m_τ and τ_τ, were measured at *BABAR* and Belle.
- Recent studies of CPV in the $\tau^- \to \pi^- K^0_S (\geq \pi^0)\nu_\tau$ decays at *BABAR* as well as in the $\tau^- \to K^0_S \pi^- \nu_\tau$ decay at Belle provide complementary information about CPV in these decays and rise a special interest to the study of the $\tau \to K^0_S \pi^- \pi^0 \nu_\tau$ decay.
- Lots of ongoing τ analyses at B factories (τEDM, $\tau \to \ell\ell'^+\ell'^-\nu\nu, \tau \to \pi\ell^+\ell^-\nu$, $\tau \to hhh\nu, \tau \to \pi\pi^+\pi^-\pi^0\nu$,...).
- **Broad τ physics program with $\times$50 statistics expected from Belle II e^+e^- Super Flavor Factory in the next decade (*see talk about Belle II by Changzheng Yuan on June 29th*).**

Backup slides

Michel parameters

$$\rho = \frac{3}{4} - \frac{3}{4}\left(|g^V_{LR}|^2 + |g^V_{RL}|^2 + 2|g^T_{LR}|^2 + 2|g^T_{RL}|^2 + \Re(g^S_{LR}g^{T*}_{LR} + g^S_{RL}g^{T*}_{RL})\right)$$

$$\eta = \frac{1}{2}\Re\left(6g^V_{RL}g^{T*}_{LR} + 6g^V_{LR}g^{T*}_{RL} + g^S_{RR}g^{V*}_{LL} + g^S_{RL}g^{V*}_{LR} + g^S_{LR}g^{V*}_{RL} + g^S_{LL}g^{V*}_{RR}\right)$$

$$\xi = 4\Re(g^S_{LR}g^{T*}_{LR}) - 4\Re(g^S_{RL}g^{T*}_{RL}) + |g^V_{LL}|^2 + 3|g^V_{LR}|^2 - 3|g^V_{RL}|^2 - |g^V_{RR}|^2 +$$

$$+5|g^T_{LR}|^2 - 5|g^T_{RL}|^2 + \frac{1}{4}|g^S_{LL}|^2 - \frac{1}{4}|g^S_{LR}|^2 + \frac{1}{4}|g^S_{RL}|^2 - \frac{1}{4}|g^S_{RR}|^2$$

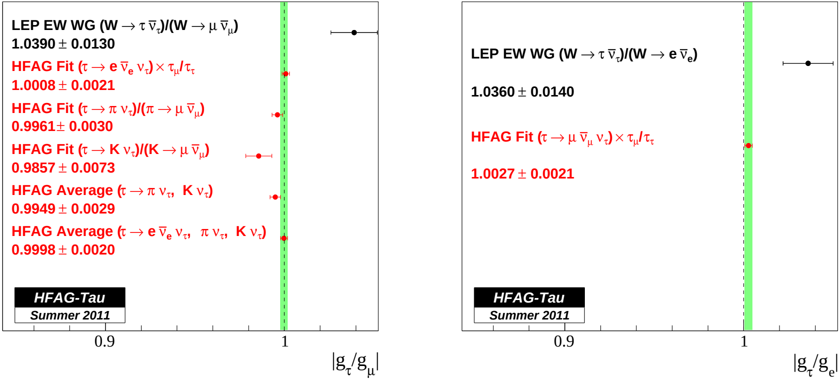
$$\xi\delta = \frac{3}{16}|g^S_{LL}|^2 - \frac{3}{16}|g^S_{LR}|^2 + \frac{3}{16}|g^S_{RL}|^2 - \frac{3}{16}|g^S_{RR}|^2 - \frac{3}{4}|g^T_{LR}|^2 + \frac{3}{4}|g^T_{RL}|^2 +$$

$$+\frac{3}{4}|g^V_{LL}|^2 - \frac{3}{4}|g^V_{RR}|^2 + \frac{3}{4}\Re(g^S_{LR}g^{T*}_{LR}) - \frac{3}{4}\Re(g^S_{RL}g^{T*}_{RL})$$

$$\bar{\eta} = \left|g^V_{RL}\right|^2 + \left|g^V_{LR}\right|^2 + \frac{1}{8}\left(\left|g^S_{RL} + 2g^T_{RL}\right|^2 + \left|g^S_{LR} + 2g^T_{LR}\right|^2\right) + 2\left(\left|g^T_{RL}\right|^2 + \left|g^T_{LR}\right|^2\right)$$

$$\xi\kappa = \left|g^V_{RL}\right|^2 - \left|g^V_{LR}\right|^2 + \frac{1}{8}\left(\left|g^S_{RL} + 2g^T_{RL}\right|^2 - \left|g^S_{LR} + 2g^T_{LR}\right|^2\right) + 2\left(\left|g^T_{RL}\right|^2 - \left|g^T_{LR}\right|^2\right)$$

Recent test of lepton universality at LEP



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**

- 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.

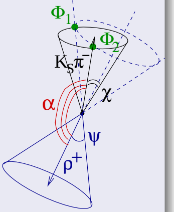
$$\frac{d\sigma(\vec\zeta^*,\vec\zeta'^*)}{d\Omega_\tau} = \frac{\alpha^2}{64E_\tau^2}\beta_\tau(D_0 + D_{ij}\zeta_i^*\zeta_j'^*),\quad \frac{d\Gamma(\tau^\pm(\vec\zeta'^*) \to \rho^\pm\nu)}{dm^2_{\pi\pi}\,d\Omega^*_\rho\,d\tilde\Omega_\pi} = A' \mp \vec B'\vec\zeta'^*$$

$$\frac{d\Gamma(\tau^\mp(\vec\zeta^*) \to (K\pi)^\mp\nu)}{dm^2_{K\pi}\,d\Omega^*_{K\pi}\,d\tilde\Omega_\pi} = \begin{matrix}(A_0 + \eta_{CP}A_1) + (\vec B_0 + \eta_{CP}\vec B_1)\vec\zeta^* \\ (A_0 + \eta^*_{CP}A_1) - (\vec B_0 + \eta^*_{CP}\vec B_1)\vec\zeta^*\end{matrix}$$

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

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

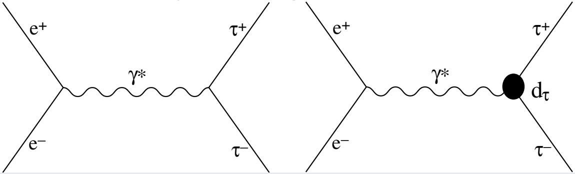
$$\frac{d\sigma((K\pi)^\mp,\rho^\pm)}{dp_{K\pi}\,d\Omega_{K\pi}\,dm^2_{K\pi}\,d\tilde\Omega_\pi\,dp_\rho\,d\Omega_\rho\,dm^2_{\pi\pi}\,d\tilde\Omega_\pi} = \sum_{\Phi_1,\Phi_2}\frac{d\sigma((K\pi)^\mp,\rho^\pm)}{dm^2_{K\pi}\,d\Omega^*_{K\pi}\,d\tilde\Omega_\pi\,dm^2_{\pi\pi}\,d\Omega^*_\rho\,d\tilde\Omega_\pi\,d\Omega_\tau}\left|\frac{\partial(\Omega^*_{K\pi},\O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



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

Electric dipole moment of τ, introduction

Electric dipole moment (EDM) of τ is strongly suppressed in the Standard Model ($\mathcal{O}(10^{-37})$ $e\cdot$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.

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

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

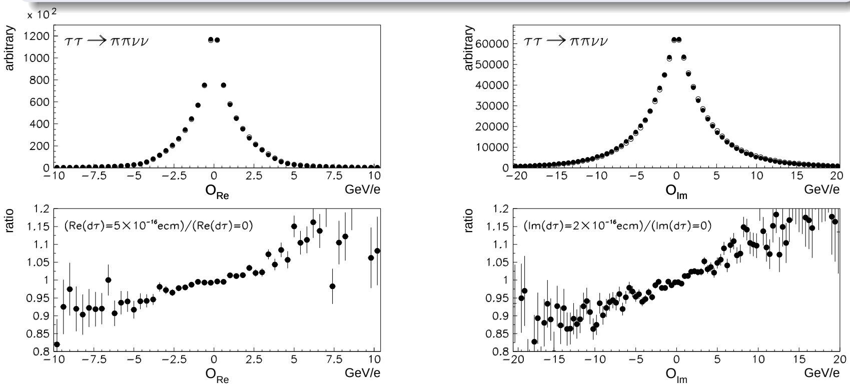
Tau EDM, method

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

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

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

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

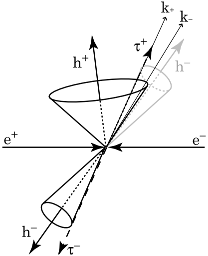


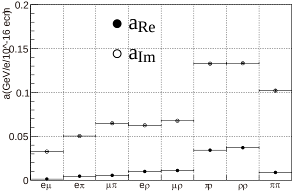
Tau EDM at Belle, data/selections

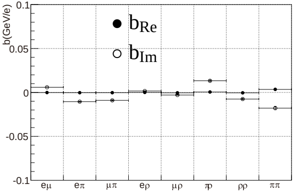
Statistics with $\int Ldt = 825$ fb^{-1} ($N_{\tau\tau} = 758 \times 10^6$) is used.
In total about 35M events are selected with the purity of 88%.

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.

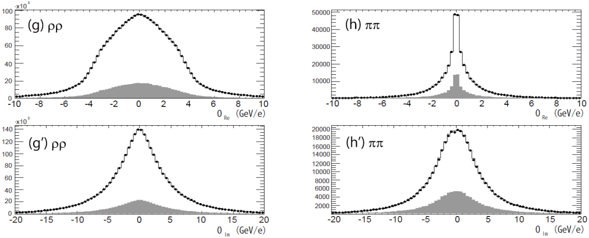
mode	yield	purity(%)	background (%)
$e\mu$	6434k	95.8	$2\gamma \to \mu\mu(2.5)$, $\tau\tau \to e\pi(1.3)$
$e\pi$	2645k	85.7	$\tau\tau \to e\rho(6.5)$ $e\mu(5.1)$ $eK^*(1.3)$
$e\rho$	7219k	91.7	$\tau\tau \to e\pi 2\pi^0(4.6)$ $eK^*(1.7)$
$\mu\pi$	2504k	80.5	$\tau\tau \to \mu\rho(6.4)$ $\mu\mu(4.9)$ $\mu K^*(1.3)$, $2\gamma \to \mu\mu(3.1)$
$\mu\rho$	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 at Belle, 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: $\Delta\mathrm{Re}(d_\tau) = 0.33 \times 10^{-17}\ e\cdot\mathrm{cm}$, $\Delta\mathrm{Im}(d_\tau) = 0.30 \times 10^{-17}\ e\cdot\mathrm{cm}$

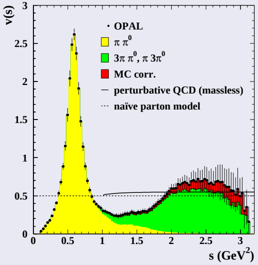
Compare with previous Belle result: PLB 551, 16 (2003) ($\int Ldt = 29.5\ \mathrm{fb}^{-1}$)

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

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

Motivation:

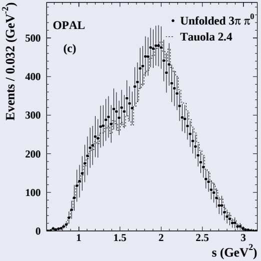
- Notable part of the **vector spectral function (v(s))** needed for the precision determination of $\alpha_s(s)$
- Test of the CVC theorem for the 4π hadronic system:
  $v(\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau) = \frac{s}{4\pi^2\alpha^2}\times$
  $\times\left(\frac{1}{2}\sigma(e^+e^- \to 2\pi^+\pi^-) + \sigma(e^+e^- \to \pi^+\pi^-2\pi^0)\right)$
- 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**

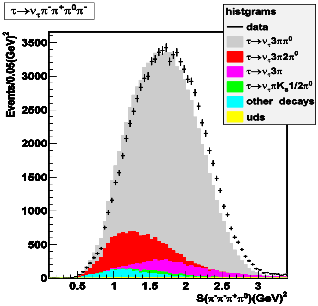


Study of $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ at Belle (I)

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, $\sum\limits_{\mathrm{ntrk}=1}^{4} Q_i = 0$.
- Event is separated into two hemispheres in CMS: Thrust>0.9, $35^\circ < \theta^{\mathrm{CMS}}_{\mathrm{thrust}} < 145^\circ$.
- Tag side: 1 track identified as e or μ.
- Signal side: 3 tracks identified as pions, and π^0 candidate with $-6 < \frac{m_{\gamma\gamma} - m_{\pi^0}}{\sigma_{\gamma\gamma}} < 5$.
- $E^{\mathrm{LAB}}_{\gamma extra} < 0.2$ 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.

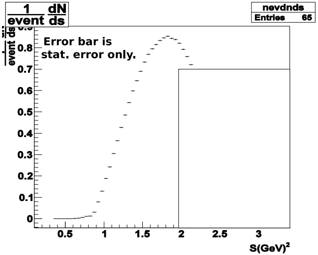
Study of $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ at Belle (II)

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

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

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$^2/c^4$.