Tau physics at Super B factory

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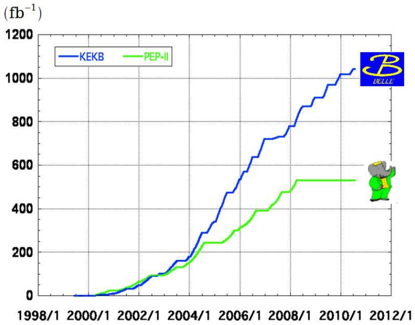
Outline:

1. Introduction, tau decays with leptons
2. Leptonic tau decays
3. Radiative leptonic tau decays
4. Tau decays into 5 leptons
5. Tau lifetime
6. LFV tau decays
7. Summary

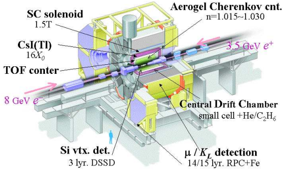
Integrated luminosity of B factories



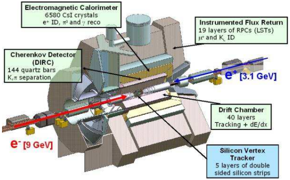
> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

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

Belle Detector



BABAR detector



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

Introduction: B as τ factory

- The world largest statistics of τ leptons $\sim 3 \times 10^9$ collected at Belle and BaBar opens the new era in precision tests of the SM in τ decays.
- In the SM charged weak interaction is described by the exchange of $W^{\pm}$ with a pure vector coupling to only left-handed fermions providing "V-A$\otimes$ V-A" Lorentz structure of the effective four-fermion weak interaction (maximal parity violation).
- Deviations from "V-A" can originate from:
  - CPV in leptonic sector.
  - Scalar contributions from $H^{\pm}$
  - Mixing of right-handed and left-handed vector currents (W_L and W_R).
- There are two main classes of tau decays:
  - Decays with leptons: $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$, $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau \gamma$, $\tau^- \to \ell^- \ell'^+ \ell'^- \bar{\nu}_\ell \nu_\tau$, $\ell, \ell' = e, \mu$
  - Hadronic decays
- Decays with leptons provide clean laboratory to probe electroweak couplings, which is complementary/competitive to $\mu^- \to e^- \bar{\nu}_e \nu_\mu (\gamma)$ (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

Leptonic τ (μ) decay

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

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

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

Ten coupling constants g^N_{ij}:

$g^S_{RR},\ g^S_{RL},\ g^S_{LR},\ g^S_{LL},\ g^V_{RR},\ g^V_{RL},\ g^V_{LR},\ g^V_{LL},\ g^T_{RL},\ g^T_{LR}.$

The indices i and j label the right or left chirality (R, L) of the charged leptons. For a given i, j and N, the chiralities of the neutrinos (n, m) are fixed. Couplings can be complex, with arbitrary total phase $\rightarrow$ 19 independent parameters.

In the SM the only non-zero coupling constant is $g^V_{LL} = 1$.

$L^- \to \ell^- \bar{\nu}_\ell \nu_L$ ($L = \tau, \mu$)

Without measuring neutrinos and spin of the outgoing charged lepton ($\ell^\mp$), only four bilinear combinations of g^N_{ij} are experimentally accessible. They are called Michel parameters (MP): ρ, η, ξ and δ. They appear in the energy spectrum of the outgoing lepton:

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

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

- $x = \frac{E_\ell}{E_{max}}$, $E_{max} = \frac{M_L}{2}(1 + \frac{m_\ell^2}{M_L^2})$, $x_0 = \frac{m_\ell}{E_{max}}$;
- θ_ℓ - angle between L spin and $\vec{p}_\ell$;
- P_L - L polarization

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

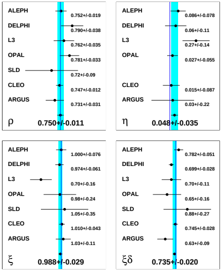
Status of Michel parameters in μ decays

Michel par.	Measured value	Experiment	SM value
ρ	$0.74977 \pm 0.00012 \pm 0.00023$ 0.026%	TWIST-11	3/4
η	$0.071 \pm 0.037 \pm 0.005$ 3.7%	ETH,JAGL,PSI-05	0
$\mathcal{P}^{\pi}_{\mu}\xi$	$1.00084 \pm 0.00029 \pm^{0.00165}_{0.00063}$ 0.17%	TWIST-11	1
δ	$0.75049 \pm 0.00021 \pm 0.00027$ 0.034%	TWIST-11	3/4
$\bar{\eta}$	-0.014 ± 0.090 8%	ELEC-84	0
ξ'	0.998 ± 0.045 4.5%	CNTR-85	1

The uncertainty of $\sim 3 \times 10^{-4}$ is achieved by TWIST for ρ and δ MP !

$\bar{\eta}$ and ξ' are measured in radiative leptonic decays.

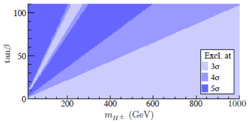
Michel par.	Measured value	Experiment	SM value
ρ (e or μ)	$0.747 \pm 0.010 \pm 0.006$ **1.2%**	CLEO-97	3/4
η (e or μ)	$0.012 \pm 0.026 \pm 0.004$ **2.6%**	ALEPH-01	0
ξ (e or μ)	$1.007 \pm 0.040 \pm 0.015$ **4.3%**	CLEO-97	1
$\xi\delta$ (e or μ)	$0.745 \pm 0.026 \pm 0.009$ **2.8%**	CLEO-97	3/4
ξ_h (all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



Belle+BaBar statistics allows us to improve uncertainties by one order of magnitude.

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

In the Type II 2HDM: $\eta_\mu(\tau) = \frac{m_\mu M_\tau}{2}\left(\frac{\tan^2\beta}{M^2_{H^\pm}}\right)^2$; $\frac{\eta_\mu(\tau)}{\eta_e(\mu)} = \frac{M_\tau}{m_e} \approx 3500$

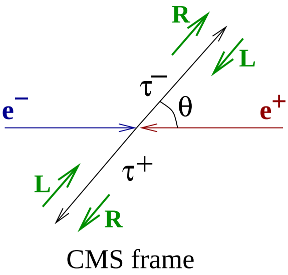


With $B \to D^{(*)}\tau\nu$ BaBar excluded Type II 2HDM in the full parameter space at the level of 3σ

To measure ξ and δ MP we have to know τ spin direction. Effect of τ spin-spin correlation in $e^+e^- \to \tau^+(\vec{\zeta}^+)\tau^-(\vec{\zeta}^-)$ can be used:

$$\frac{d\sigma(\vec{\zeta}^-,\vec{\zeta}^+)}{d\Omega} = \frac{\alpha^2}{64E_\tau^2}\beta_\tau(D_0 + D_{ij}\zeta_i^-\zeta_j^+)$$

$$D_0 = 1 + \cos^2\theta + \frac{1}{\gamma_\tau^2}\sin^2\theta$$

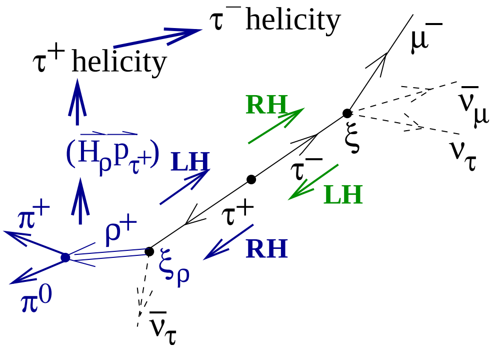


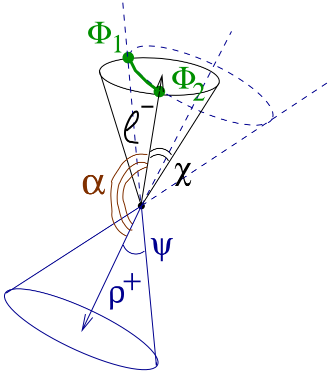
$$D_{ij} = \begin{pmatrix} (1+\frac{1}{\gamma_\tau^2})\sin^2\theta & 0 & \frac{1}{\gamma_\tau}\sin 2\theta \\ 0 & -\beta_\tau^2\sin^2\theta & 0 \\ \frac{1}{\gamma_\tau}\sin 2\theta & 0 & 1+\cos^2\theta - \frac{1}{\gamma_\tau^2}\sin^2\theta \end{pmatrix}$$

τ^- and τ^+ helicities are 95% anti-correlated, so if we know helicity of τ on the tag side we can identify helicity of τ on the signal side.

- $\tau^{\mp}\to\ell^{\mp}\nu\nu$ vs. $\tau^{\pm}\to\rho^{\pm}\nu$ to measure MP: ρ, η, $\xi_\rho\xi$, $\xi_\rho\xi\delta$
- $\tau^{\mp}\to\rho^{\mp}\nu$ vs. $\tau^{\pm}\to\rho^{\pm}\nu$ to measure ξ_ρ^2

In the $\ell-\rho$ events $\tau\to\rho(\to\pi\pi^0)\nu$ serves as spin-analyzer





In the $\ell-\rho$ events the direction of τ axis is constrained by arc, which is determined by measurable angles:

$$\Phi_1=\pi+\arcsin\left(\frac{\cos\psi\cos\alpha+\cos\chi}{\sin\psi\sin\alpha}\right),\ \Phi_2=2\pi-\arcsin\left(\frac{\cos\psi\cos\alpha+\cos\chi}{\sin\psi\sin\alpha}\right)$$

Method: theoretical framework

- W. Fetscher, Phys. Rev. D 42 (1990) 1544.
  $\ell_1^{\mp} - \ell_2^{\pm}$, $\ell^{\mp} - h^{\pm}$, $\ell = e,\ \mu;\ h = \pi,\ K.$
- K. Tamai, Nucl. Phys. B 668 (2003) 385; KEK Preprint 2003-14
  $\ell^{\mp} - \rho^{\pm}(\to \pi^{\pm}\pi^0)$

$$\frac{d\sigma(\vec{\zeta},\vec{\zeta}')}{d\Omega} = \frac{\alpha^2}{64E_\tau^2}\beta_\tau(D_0 + D_{ij}\zeta_i\zeta_j')$$

$$\frac{d\Gamma(\tau^{\mp}(\vec{\zeta}^*) \to \ell^{\mp}\nu\nu)}{dx^* d\Omega_\ell^*} = \kappa_\ell(A(x^*) \mp \xi\vec{n}_\ell^*\vec{\zeta}^* B(x^*)),\ x^* = E_\ell^*/E_{\ell\max}^*$$

$$A(x^*) = A_0(x^*) + \rho A_1(x^*) + \eta A_2(x^*),\ B(x^*) = B_1(x^*) + \delta B_2(x^*)$$

$$\frac{d\Gamma(\tau^{\pm}(\vec{\zeta'}^*) \to \rho^{\pm}\nu)}{dm_{\pi\pi}^2 d\Omega_\rho^* d\tilde{\Omega}_\pi} = \kappa_\rho(A' \mp \xi_\rho\vec{B'}\vec{\zeta'}^*)W(m_{\pi\pi}^2)$$

$$A' = 2(q,Q)Q_0^* - Q^2 q_0^*,\ \vec{B'} = Q^2\vec{K}^* + 2(q,Q)\vec{Q}^*,\ W = |F_\pi(m_{\pi\pi}^2)|^2\frac{p_\rho(m_{\pi\pi}^2)\tilde{p}_\pi(m_{\pi\pi}^2)}{M_\tau m_{\pi\pi}}$$

$$\frac{d\sigma(\ell^{\mp},\rho^{\pm})}{dE_\ell^* d\Omega_\ell^* d\Omega_\rho^* dm_{\pi\pi}^2 d\tilde{\Omega}_\pi d\Omega_\tau} = \kappa_\ell\kappa_\rho\frac{\alpha^2\beta_\tau}{64E_\tau^2}(D_0 A' A(E_\ell^*) + \xi_\rho\xi_\ell D_{ij} n_{\ell i}^* B_j' B(E_\ell^*))W(m_{\pi\pi}^2)$$

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

Method: unbinned maximum likelihood fit

4 Michel parameters ($\vec{\Theta} = (1,\ \rho,\ \eta,\ \xi_\rho\xi_\ell,\ \xi_\rho\xi_\ell\delta_\ell)$) are extracted in the unbinned maximum likelihood fit of $\ell - \rho$ events in the 9D phase space ($\vec{z} = (p_\ell,\ \cos\theta_\ell,\ \phi_\ell,\ p_\rho,\ \cos\theta_\rho,\ \phi_\rho,\ m_{\pi\pi},\ \cos\tilde{\theta}_\pi,\ \tilde{\phi}_\pi)$) in CMS.
The PDF for individual k-th event is written in the form:

$$\mathcal{P}^{(k)} = \frac{\mathcal{F}(\vec{z}^{(k)})}{\mathcal{N}(\vec{\Theta})},\ \mathcal{F}(\vec{z}) = \frac{d\sigma(\ell^\mp, \rho^\pm)}{dp_\ell d\Omega_\ell dp_\rho d\Omega_\rho dm^2_{\pi\pi} d\tilde{\Omega}_\pi},\ \mathcal{N}(\vec{\Theta}) = \int \mathcal{F}(\vec{z})d\vec{z}$$

Likelihood function for N events:

$$L = \prod_{k=1}^{N} \mathcal{P}^{(k)},\ \mathcal{L} = -\ln L = N \ln \mathcal{N}(\vec{\Theta}) - \sum_{k=1}^{N} \ln \mathcal{F}^{(k)},\ \mathcal{F}^{(k)} = \mathcal{F}(\vec{z}^{(k)})$$

$$\mathcal{F}^{(k)} = A_0^{(k)}\Theta_0 + A_1^{(k)}\Theta_1 + A_2^{(k)}\Theta_2 + A_3^{(k)}\Theta_3 + A_4^{(k)}\Theta_4 = \sum_{i=0}^{4} A_i^{(k)}\Theta_i,\ \mathcal{N}(\vec{\Theta}) = \sum_{i=0}^{4} C_i\Theta_i$$

$$\mathcal{L} = N \ln(C_i\Theta_i) - \sum_{k=1}^{N} \ln(A_i^{(k)}\Theta_i)$$

As a result fitted statistics is represented by a set of $5 \times N$ values of $A_i^{(k)}$ ($k = 1 \div N,\ i = 0 \div 4$), which is calculated only once. C_i ($i = 0 \div 4$) are calculated using MC simulation.

Physical corrections, detector effects, backgrounds

Physical corrections:

- Initial state radiation (ISR) $e^+e^- \to \tau^+\tau^-\gamma_{\rm ISR}$
- Radiative leptonic decays $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau\gamma$
- $\tau^- \to \pi^-\pi^0\nu_\tau\gamma$
- Photon polarisation operator $\Pi(s)$
- Beam energy spread

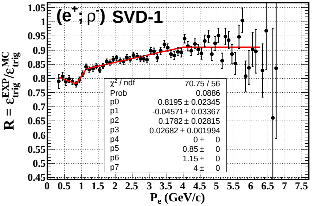
Detector effects:

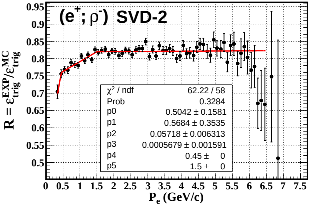
- Track momentum resolution
- γ energy and angular resolution
- Effect of external bremsstrahlung for $e-\rho$ events

Background:
The main background comes from $\ell-\pi\pi^0\pi^0$(~10%) and $\pi-\pi\pi^0(\pi\to\mu)$(~1.5%) events. The remaining background(~2.0%) is taken into account using MC-based approach.

$$\mathcal{P}_{\rm TOT} = (1-\lambda_{3\pi}-\lambda_{\pi}-\lambda_{\rm other})\mathcal{P}^{\rm signal}+\lambda_{3\pi}\mathcal{P}^{\rm BG}_{3\pi}+\lambda_{\pi}\mathcal{P}^{\rm BG}_{\pi}+\lambda_{\rm other}\mathcal{P}^{\rm BG}_{\rm other}(\rm MC)$$

- The procedure has been developed and tested with large MC sample. Statistical accuracy of $\sim 0.1\%$ is achieved with Belle data.
- The main challenge is to reach the comparable systematic uncertainty:
  - Nonuniformity of the trigger efficiency for events with large energy deposition in calorimeter, problem with "Bhabha veto" trigger argument
  - EXP/MC efficiency corrections: track reconstruction, lepton identification, pion identification, π^0 reconstruction efficiency

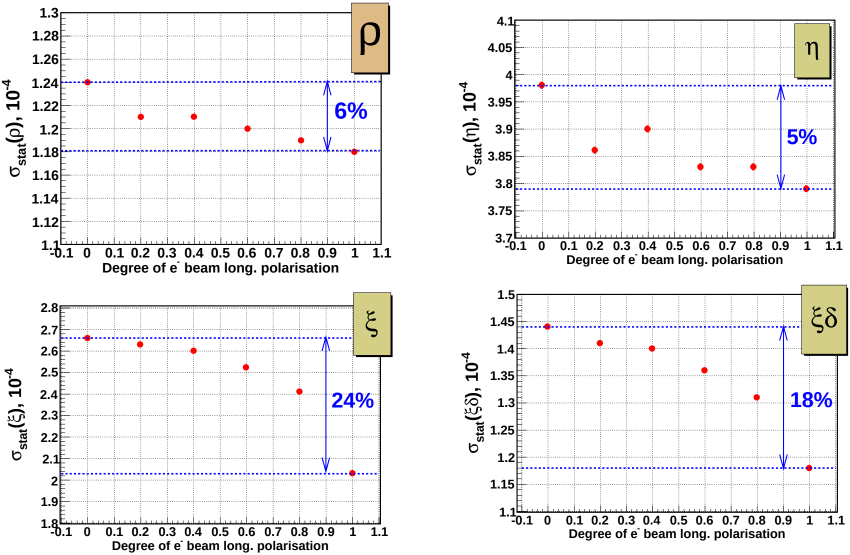




Much higher statistics ($\times 50$), better detector performance and more intellectual trigger of the coming Super B factory, Belle II, will allow us to improve systematic uncertainties. Expected statistical uncertainty is of the order of 10^{-4}, which is competitive with the most precision results obtained by TWIST collaboration.

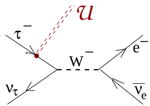
Sensitivities to MP at Belle II

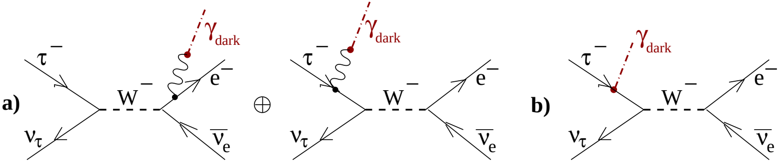
Shota Nagumo (The University of Tokyo)



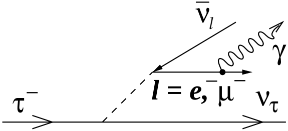
There are many New Physics models, which predict the distortion of lepton energy spectrum:

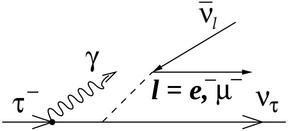
- Tensor interaction: $\mathcal{L} = \frac{g}{2\sqrt{2}} W^{\mu} \left\{ \bar{\nu}\gamma_{\mu}(1-\gamma^5)\tau + \frac{\kappa_\tau^W}{2m_\tau}\partial^{\nu}\left(\bar{\nu}\sigma_{\mu\nu}(1-\gamma^5)\tau\right)\right\}$ was studied previously only by DELPHI (LEP): $-0.096 < \kappa_\tau^W < 0.037$: Abreu EPJ C16 (2000) 229.
- Unparticles: Moyotl PRD 84 (2011) 073010. Choudhury PLB 658 (2008) 148.
- Lorentz and CPTV: Hollenberg PLB 701 (2011) 89
- Dark Sector (arXiv:1311.0029 [hep-ph]), for example dark photon:





We encourage theorists to develop formalisms (form factors) needed for the tests of promising New Physics models in leptonic τ 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:

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

	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 plan to measure $\bar{\eta}$ and $\xi\kappa$ in radiative leptonic τ decays at Belle, the expected accuracy is $1 \div 2\%$. At Belle II the expected statistical uncertainties of $\bar{\eta}$ and $\xi\kappa$ are of the order of 10^{-3}.

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.

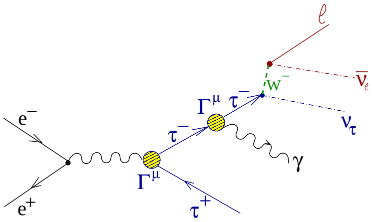
- Study of the dynamics of radiative leptonic τ decays at Belle+BaBar/Belle II is fully competitive with the measurements done in the experiments with muon beams.
- $\bar{\eta}$ and $\xi\kappa$ have not been measured in τ decays yet.
- Michel parameters formalism for τ radiative leptonic decays has not been completely developed. Form factors h_0, h_1, g_0, g_1 were calculated only in the massless limit (for outgoing lepton). To study $\tau^- \to \mu^- \nu_\tau \bar{\nu_\mu} \gamma$ terms with $r = \frac{m_\mu}{m_\tau}$ should be also kept.
- We encourage theorists to revise Michel parameters formalism for radiative leptonic τ decays taking into account effect of the finite mass of the outgoing lepton. Different scenarios for the massive dark photon production in leptonic τ decays can be considered in parallel.

a_τ and EDM in radiative leptonic decays

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

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

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



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

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

- 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].

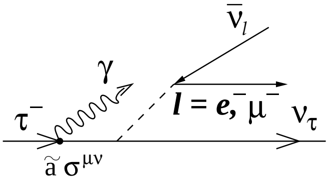
It was suggested to search for the a_τ in the $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau \gamma$ using the phenomenon of radiation zero: in the vicinity of $\cos(\ell,\gamma) = -1$, $x = 2E_\ell/m_\tau = 1 + \frac{m_\ell^2}{m_\tau^2}$ term $\sim a_\tau^2$ dominates.

Effective interaction

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

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

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



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

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 $(\tau^\mp \to \ell^\mp\nu\nu\gamma;\ \tau^\pm \to h^\pm\nu)$, $h = e,\ \mu,\ \pi,\ \pi\pi^0,\ \pi2\pi^0, 3\pi$ (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

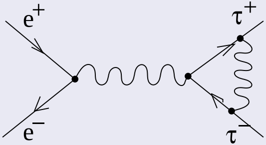
J. Abdallah et al. [DELPHI Collaboration], Eur. Phys. J. C 35 (2004) 159

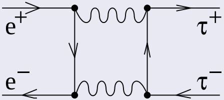
$-0.052 < a_\tau < 0.013$ (CL = 95%) in $e^+e^- \to e^+e^-\tau^+\tau^-$

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 $e^+e^- \to \tau^+\tau^-$

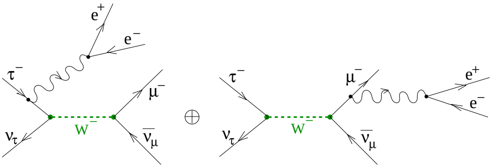
To measure a_τ in the $\tau^+\tau^-$ production vertex the procedure to take into account box diagrams should be developed.





We ask theorists to investigate the possibilty to calculate box diagrams and provide us formalism for the $e^+e^- \to \tau^+\tau^-$ full differential cross section needed for precision measurement of a_τ at Belle/Belle II

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

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

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

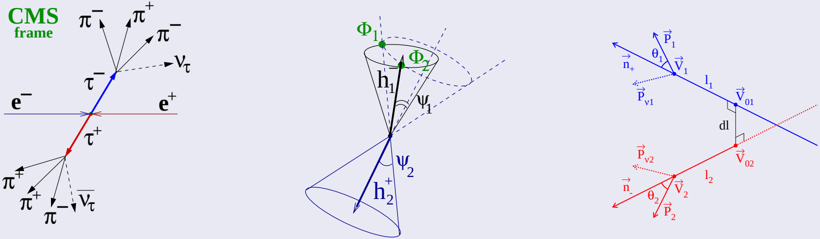
$$\frac{d\Gamma(\tau)}{d\mathcal{PS}} = Q_{LL}d_1 + Q_{LR}d_2 + Q_{RL}d_3 + Q_{RR}d_4 + B_{RL}d_5 + B_{LR}d_6$$

Up to now Q_{LL}, Q_{LR}, Q_{RL}, Q_{RR}, B_{RL}, B_{LR} were measured only in muon decays ($\mu \to eee\nu\nu$) with the accuracy of about 10% and worse. We can measure these parameters with the accuracy of $\sim 10\%$ at Belle, and $1 \div 2\%$ at Belle II in τ decays.

We encourage theorists to perform analytical calculation of all form factors in the differential decay width for τ decay into 5 leptons taking into account effects of the finite masses of the outgoing leptons.

$\tau^+\tau^-$ prod. vertex at B factory, τ lifetime

Asymmetric-energy layout of experiment allows us to determine $\tau^+\tau^-$ production point in LAB independently from the position of beam IP.



- We analysed $e^+e^- \to \tau^+\tau^- \to (\pi^+\pi^+\pi^-\bar{\nu}_\tau,\ \pi^+\pi^-\pi^-\nu_\tau)$ events to measure τ lifetime at Belle
- τ momentum direction is determined with two-fold ambiguity in CMS, average axis is used.
- Tau decay vertex can be reconstructed for the modes with at least 3 charged particles

At the asymmetric-energy e^+e^- collider it is possible to measure time-dependent CP asymmetries for the τ decay modes with at least 3 charged particles in the final state. Are there some promising New Physics models which can be tested with these asymmetries ?

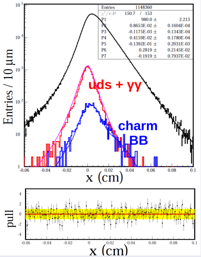
τ lifetime

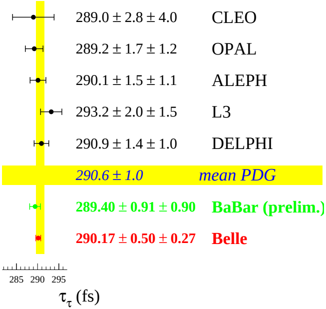
K. Belous et al. [Belle Collab.], PRL 112, 031801 (2014)

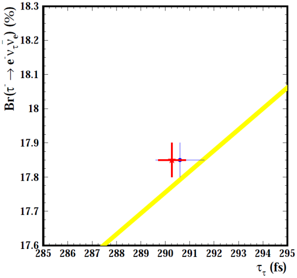
$$c\tau_\tau = (86.99 \pm 0.16(\text{stat.}) \pm 0.10(\text{syst.}))\ \mu\text{m}.$$

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

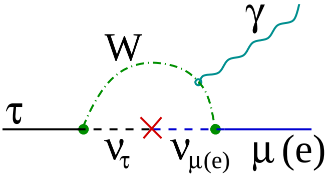
$$|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\text{average}} < 7.0 \times 10^{-3}\ \text{at } 90\%\ \text{CL}.$$







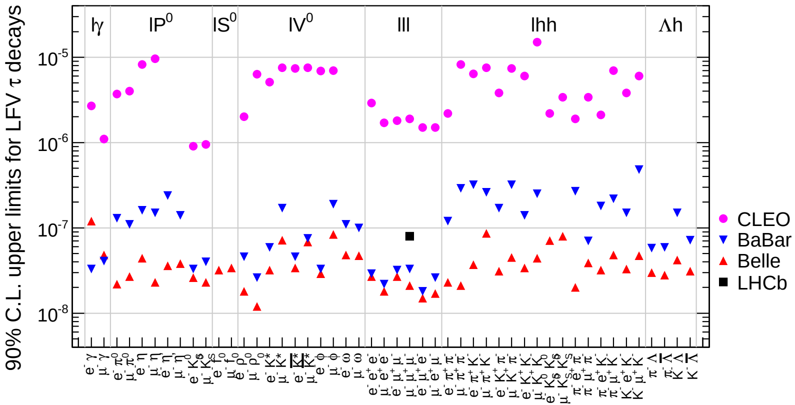
LFV tau decays



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 (SM), $\mathcal{B}(\tau \to \ell\nu) \sim \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 < 10^{-54}$
- 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.

LFV decays of τ



48 different LFV modes were studied at Belle and BaBar

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

Summary

- Much higher statistics ($\times 50$) and better detector performance of the coming Belle II experiment will allow us to improve precision tests of the Standard Model and BSM. Tau decays into leptons provide clean laboratory to test SM at the level of precision competitive with the accuracies achieved in the experiments with muon beams.
- Leptonic tau decays allow us to measure four Michel parameters (MP): ρ, η, ξ, δ. Statistical accuracy of MP at Belle II approaches 10^{-4} level. Many New Physics models can be tested/constrained, but great help from theorists is needed to develop necessary formalisms.
- Radiative leptonic tau decays allow us to measure two additional Michel parameters: $\bar{\eta}$ and κ. At Belle II they can be measured with the accuracy better than 1%. Anomalous magnetic moment of τ can be measured in radiative leptonic decays at Belle II with the accuracy compatible with the current best measurement done by DELPHI.
- Tau decays into 5 leptons represent additional very attractive possibility to test SM through Q_{LL}, Q_{LR}, Q_{RL}, Q_{RR}, B_{LR} and B_{RL} Michel parameters. At Belle II accuracy of about few percent can be achieved.
- At Belle II LFV tau decays will allow us to search for the effects of various New Physics models on the level of $\mathcal{B} = 10^{-9} \div 10^{-10}$.