Tau Michel parameters at Belle II

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Introduction

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:

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

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

Ten couplings g^N_{ij}, in the SM the only non-zero constant is $g^V_{LL} = 1$

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

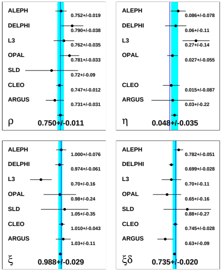
$$\frac{d\Gamma(\tau^\mp)}{d\Omega dx} = \frac{4G_F^2 M_\tau E_{\max}^4}{(2\pi)^4}\sqrt{x^2-x_0^2}\Big(x(1-x)+\frac{2}{9}\rho(4x^2-3x-x_0^2)+\eta x_0(1-x)$$

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

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



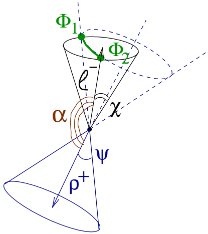
With ×300 Belle statistics we can improve MP uncertainties by one order of magnitude

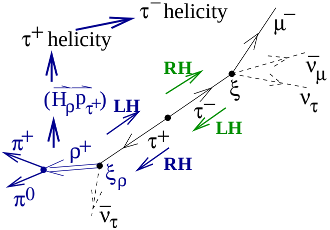
In BSM models the couplings to τ are expected to be enhanced in comparison with μ.
Also contribution from New Physics in τ decays can be amplified by $(\frac{m_\tau}{m_\mu})^n$.

- In the Type II 2HDM: $\eta_\mu(\tau) = \frac{m_\mu M_\tau}{2}\left(\frac{\tan^2\beta}{M^2_{H^\pm}}\right)^2$; $\frac{\eta_\mu(\tau)}{\eta_e(\mu)} = \frac{M_\tau}{m_e} \approx 3500$
- 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
- Dark Sector (arXiv:1311.0029 [hep-ph])

Method, study of $\ell - \rho$ and $\rho - \rho$ events

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.





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

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

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

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

Corrections, detector effects, background

Physical corrections:

- All $\mathcal{O}(\alpha^3)$ QED and electroweak higher order corrections to $e^+e^- \to \tau^+\tau^-$ are included
- Radiative leptonic decays $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau\gamma$
- Radiative decay $\tau^- \to \pi^-\pi^0\nu_\tau\gamma$

Detector effects:

- Track momentum resolution
- γ energy and angular resolution
- Effect of external bremsstrahlung for $e - \rho$ events
- Beam energy spread
- EXP/MC efficiency corrections (trigger, track rec., π^0 rec., ℓID, πID)

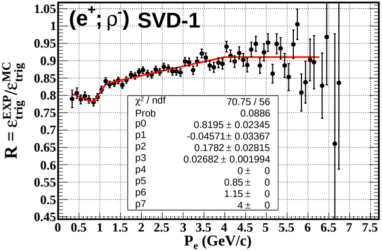
Background:

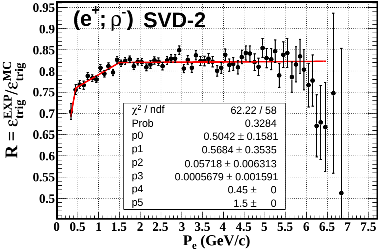
The main background comes from $\ell - \pi\pi^0\pi^0$(∼10%) and $\pi - \pi\pi^0(\pi \to \mu)$(∼1.5%) events, it is included in PDF analytically. The remaining background(∼2.0%) is taken into account using MC-based approach. Background from the non-$\tau\tau$ events is $\lesssim$ 0.1%.

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

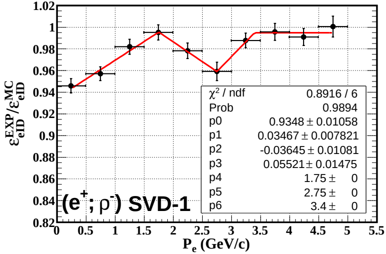
EXP/MC efficiency corrections (($e^+; \rho^-$) events)

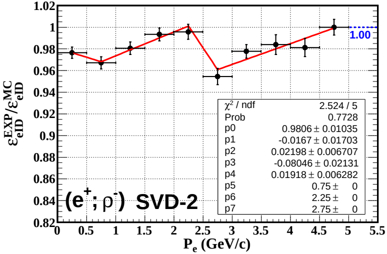
Two independent subtriggers (neutral (ECL) and charged (CDC$\oplus$TOF$\oplus$KLM)) are used to evaluate EXP/MC trigger efficiency correction.





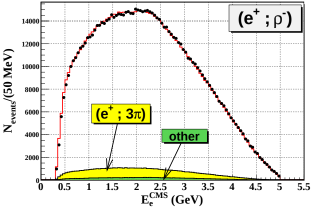
The lepton detection efficiency is corrected using the $e^+e^- \to e^+e^-\ell^+\ell^-,\ \ell = e, \mu$ two-photon data sample.

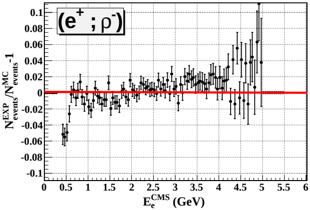




Fit of the experimental data, $(e^+; \rho^-)$

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).



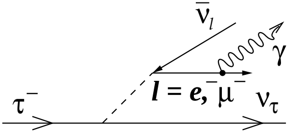


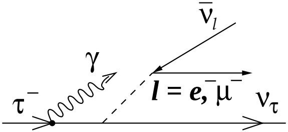
Source	$\sigma(\rho)$, %	$\sigma(\eta)$, %	$\sigma(\xi_\rho\xi)$, %	$\sigma(\xi_\rho\xi\delta)$, %
Physical corrections				
ISR+$\mathcal{O}(\alpha^3)$	0.10	0.30	0.20	0.15
$\tau \to \ell\nu\nu\gamma$	0.03	0.10	0.09	0.08
$\tau \to \rho\nu\gamma$	0.06	0.16	0.11	0.02
Apparatus corrections				
Res. $\oplus$ 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

We observe a systematic bias of the order of a few percent, especially in the $\xi_\rho\xi$ and $\xi_\rho\xi\delta$, which originates from the remaining inaccuracies in the description of the $\ell - 3\pi$ background.

The dominant systematic uncertainties coming from the various EXP/MC efficiency corrections are under investigation.

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:

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

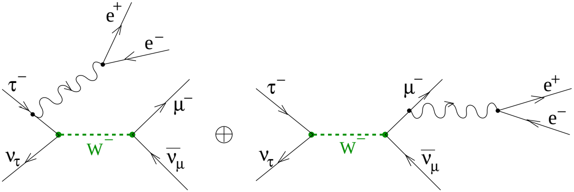
	Belle+BaBar	Belle II
$N_{sel}(e^\mp;\rho^\pm)$, 10^6	0.87	28.2
$N_{sel}(\mu^\mp;\rho^\pm)$, 10^6	0.18	5.8

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.

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].

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

$$,$$

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

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

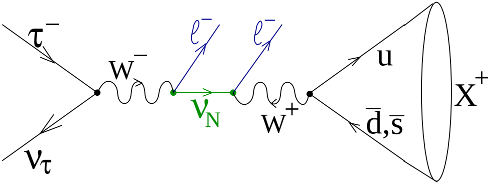
$$\sum_j U_{ej}V_{\mu j} = \overline{w_{e\mu}},\;\; \sum_k V_{ek}U_{\mu k} = \overline{w_{e\mu h}},$$

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

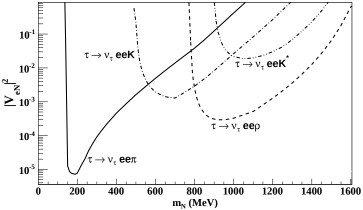
where: $U_{\ell j}/V_{\ell j}$ - left/right-chirality lepton mixing matrix, $m_{\nu D}$ and $m_{\nu R}$ are Dirac-type and right-chirality Majorana-type elements of the neutrino mass matrix.

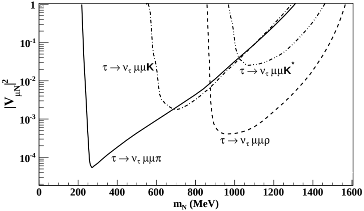
Search for heavy Majorana neutrino in τ decays II

$\tau^- \to \ell^-\ell^- X^+ \nu_\tau$ ($\ell = e,\ \nu$; $X = \pi,\ K,\ \rho,\ K^*$) 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.





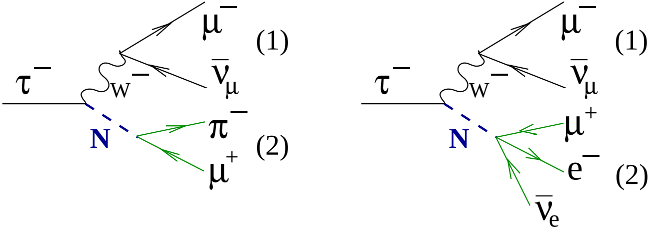
In the case of the resonant mechanism where the contribution of one heavy Majorana neutrino dominates and $\mathcal{B}$ upper limits of $\mathcal{O}(10^{-}7)$ (which can be reached at Belle II) the constraints on the $|V_{\ell N}|^2$ vs m_N plane can be obtained (competitive to the constraints from B 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, $1\times 10^{-3} \lesssim |U_{\mu N}|^2 \lesssim 4\times 10^{-3}$, $\tau_N \lesssim 1\times 10^{-9}$ s.



To explain anomaly the branching fractions must be:

$$\mathcal{B}(\tau^- \to \{\mu^-\bar{\nu}_\mu\}_1\{\mu^+\pi^-\}_2) = 2.0\times 10^{-9} \div 1.3\times 10^{-5},$$
$$\mathcal{B}(\tau^- \to \{\mu^-\bar{\nu}_\mu\}_1\{\mu^+e^-\bar{\nu}_e\}_2) = 2.1\times 10^{-8} \div 8.2\times 10^{-5}.$$

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:

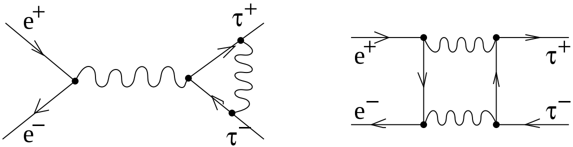
$\tau^- \to \ell^-\bar{\nu}_\ell N,\ N \to \gamma\nu$, i.e. constraints can be obtained from Michel parameters.

Tasks for the experimentalists at Belle/Belle II

- Improve the performance of the trigger for two-track events (more intellectual ECL Bhabha trigger). Develop the procedure to determine EXP/MC trigger efficiency corrections.
- Tabulate precisely EXP/MC efficiency corrections:
  - ℓID: $e^+e^- \to e^+e^-\ell^+\ell^-$, $\ell = e,\ \mu$
  - K/πID: $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+_{\rm slow}$
  - K_S reconstruction: $D^{*+} \to (D^0 \to K^0_S\pi^+\pi^-)\pi^+_{\rm slow}$
  - K_L reconstruction
  - track reconstruction: $B^0 \to (D^{*-} \to D^0\pi^-_{\rm slow})\pi^+$ (low momentum), $D^{*+} \to (D^0 \to (K^0_S \to \pi^+\pi^-)\pi^+\pi^-)\pi^+_{\rm slow}$ (high momentum)
  - γ, π^0 reconstruction: $\eta \to 3\pi^0/\eta \to 2\gamma$, $\eta \to 3\pi^0/\eta \to \pi^+\pi^-\pi^0$, $(\tau^- \to \pi^-\pi^0\nu_\tau;\ \tau^+ \to \pi^+\pi^0\bar{\nu}_\tau)$, $(\tau^- \to \pi^-\pi^0\nu_\tau;\ \tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau)$
- Include Michel parameter formalisms for several decay modes in Belle II TAUOLA generator.

Needed help from theorists

- Michel parameter formalism for radiative leptonic τ decays with effect of the finite mass of the outgoing lepton is needed (T. Mannel and S. Faller ?).
  Effect of nonzero neutrino mass.
- Analytical calculation of all form factors in the differential decay width of τ decay into 5 leptons taking into account effects of the finite masses of the outgoing leptons (P. Roig).
- Review the possibilities to study neutrinos in τ decays at the Super Flavor Factory (Search for Majorana, Sterile, BSM heavy Dirac neutrinos).
- Revise the formalism for the higher order QED (and QCD ?) corrections to the $e^+e^- \to \tau^+\tau^-$ differential cross section (with effects of tau spin-spin correlations).



S. Jadach and Z. Was, Acta Phys. Polon. B **15** (1984) 1151 [Erratum-ibid. B **16** (1985) 483].

Summary

- Much higher statistics (×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.
- Radiative leptonic τ decays allow us to measure two additional Michel parameters, $\bar{\eta}$ and κ. At Belle II they can be measured with the accuracy of about 1%.
- 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.
- In τ decays, it is also possible to study neutrino properties. Various BSM scenarios can be tested.